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METEOROLOGY FOR LAND DEVELOPMENT PLANNING IN THE TULSA METROPOLITAN AREA

Gerard A. DeMarrais

Robert A. Taft Sanitary Engineering Center
Cincinnati, Ohio

1961

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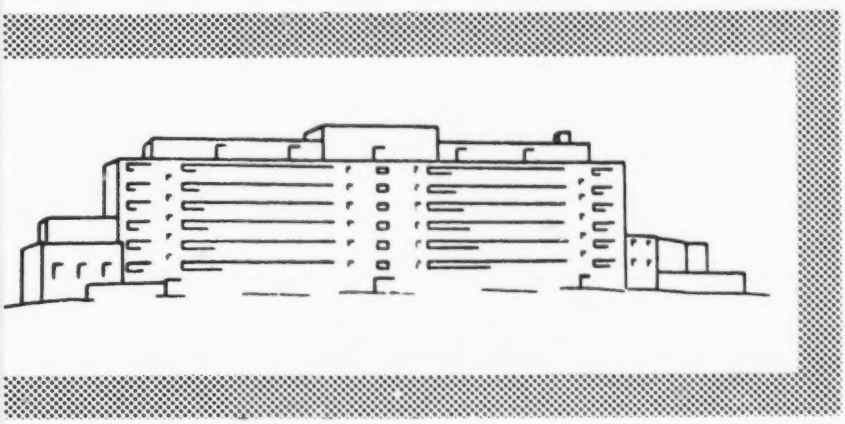

The Robert A. Taft
Sanitary Engineering Center

TECHNICAL REPORT
A61-5

U. S. DEPARTMENT OF HEALTH,
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METEOROLOGY FOR LAND DEVELOPMENT PLANNING IN THE TULSA METROPOLITAN AREA

Gerard A. DeMarrais

U. S. Weather Bureau Research Station
Laboratory of Engineering and Physical Sciences

U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
PUBLIC HEALTH SERVICE
Bureau of State Services
Division of Air Pollution

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Cincinnati 26, Ohio

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METEOROLOGY FOR LAND DEVELOPMENT PLANNING

IN THE TULSA METROPOLITAN AREA

Introduction

The purpose of this report is to provide the Tulsa Metropolitan Area Planning Commission with meteorological information which will be of assistance to the Commission in setting zoning performance standards and requirements. The data herein reported were collected during the period November 1957 through June 1960 at both a special meteorological measuring station located on the campus of the University of Tulsa and at the Weather Bureau Airport Station at Tulsa Municipal Airport.

Air Quality and Meteorology

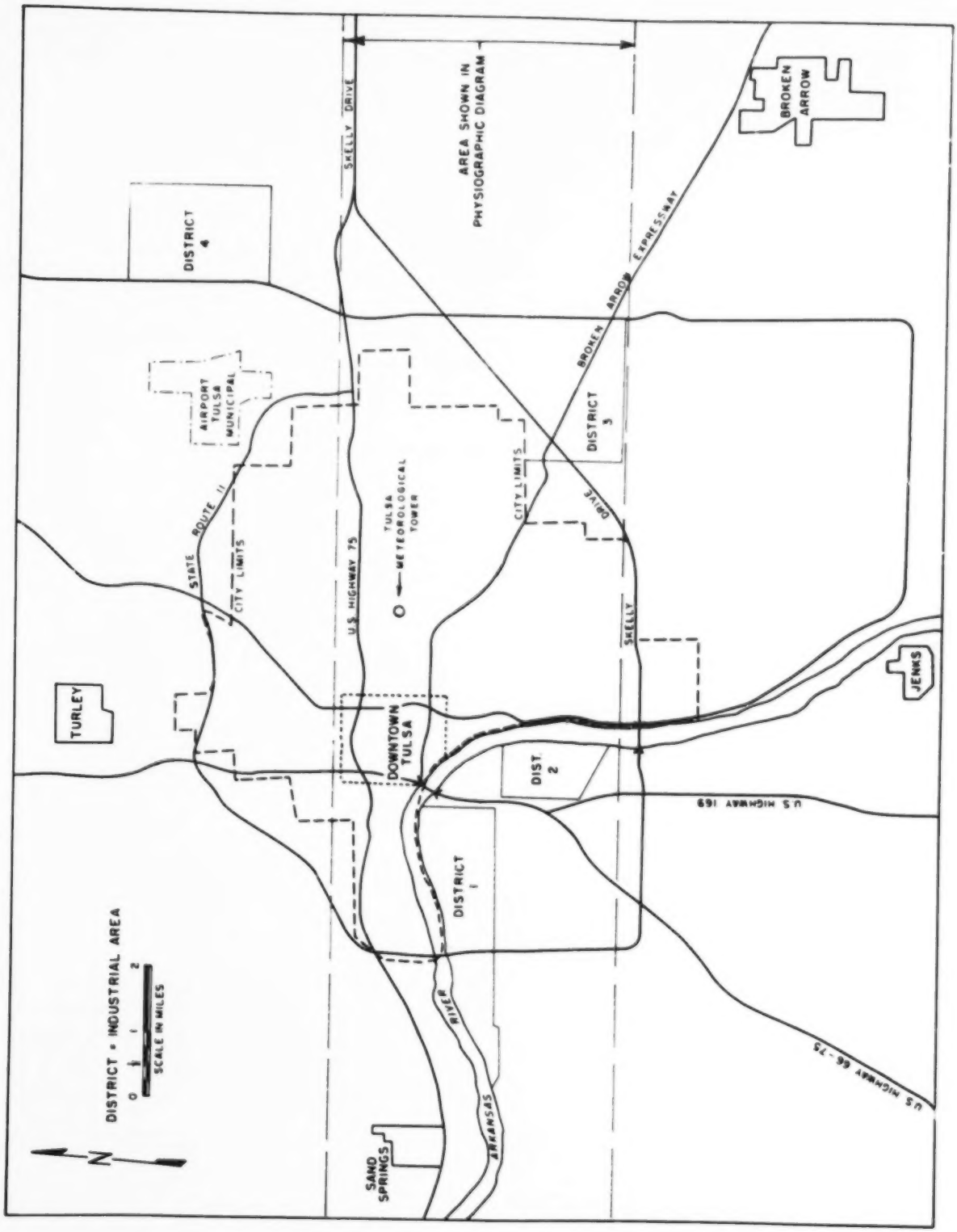
The role of meteorological factors in diluting and dispersing foreign materials released into the atmosphere has been described in detail (U. S. Weather Bureau, 1955) and the following review is concerned with only the most salient features. Effluents released into the atmosphere may be transported, diffuse, fall out, be washed out or undergo photochemical modification; more than one of these processes are usually occurring at any given time. Wind is the primary phenomenon that transports effluents. Diffusion is dependent upon characteristics of the effluents and their sources, man-made and natural topography and several meteorological parameters; winds and temperature lapse rate appear to be the most important measured meteorological parameters. The settling velocity of particles and convective currents determine fallout whereas washout is a function of precipitation phenomena. Photochemical modification is directly related to the intensity of sunshine.

In this report the following are discussed: 1) the effects of topography on observed meteorological parameters, 2) winds, 3) temperature lapse rate, 4) amount of sunshine, 5) cloudiness, and 6) precipitation.

Topography of the Tulsa Area

The broad scale features of the Tulsa area have been adequately described in the previously published A Climatic Digest for Greater Tulsa (Burt, 1958) and only those features of the local area which appear to be particularly noteworthy are presented here.

The Metropolitan Area Planning Commission envisages the development of the area bounded by Broken Arrow in the east, Sand Springs in the west, Turley in the north, and Jenks in the south. A map of the area is shown in Figure 1. The delineated area is shown in Figure 2 as a


AREA SHOWN IN PHYSIOGRAPHIC DIAGRAM
SKELLY DRIVE
BROKEN ARROW
BROKEN ARROW EXPRESSWAY
DISTRICT 4
DISTRICT 3
DISTRICT 2
DISTRICT 1
AIRPORT TULSA MUNICIPAL
STATE ROUTE 11
CITY LIMITS
U.S. HIGHWAY 75
TULSA METEOROLOGICAL TOWER
CITY LIMITS
SKELLY
TURLEY
DOWNTOWN TULSA
JENKS
U.S. HIGHWAY 169
U.S. HIGHWAY 66 - 75
ARKANSAS RIVER
SAND SPRINGS
DISTRICT = INDUSTRIAL AREA
0 1 2
SCALE IN MILES
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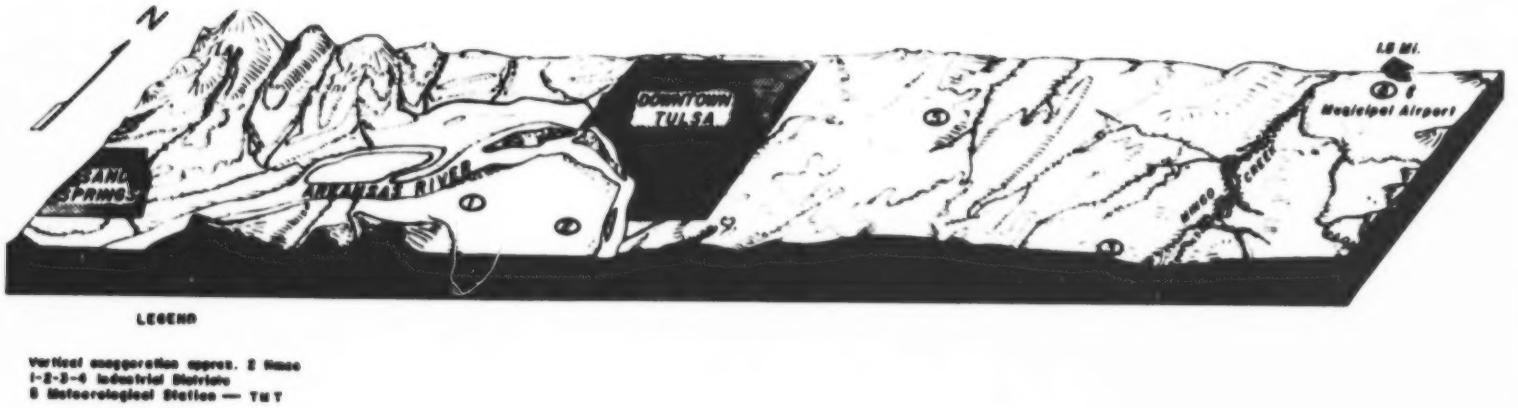


Figure 2. PHYSIOGRAPHIC DIAGRAM, TULSA AREA

Figure 3. VIEW OF DOWNTOWN TULSA AS SEEN FROM WEST TULSA

physiographic diagram. The eastern part of the metropolitan area is seen to be relatively flat, whereas the western section has numerous small hills and valleys. Man-made topography is depicted in Figure 3 which shows the city of Tulsa as viewed from the west. The only high structures are in the relatively small center of the downtown area of Tulsa. In the residential area most of the homes are only one story high and are not built close to one another.

Unfortunately meteorological observations have been made at only a few locations in the Tulsa area. However, on the basis of studies made in areas with similar topography the effects of the terrain of the Tulsa area on meteorological parameters may be inferred.

The flat lands are the developed areas, and these with all their combustion processes, stone, concrete and asphalt surfaces are heat sources that not only raise the ambient air temperature but also affect the horizontal and vertical temperature gradients (Duckworth, 1954). The industrial and business centers of the heat sources may act as heat islands or areas from which temperatures decrease outward.

In addition the diurnal variation of vertical temperature differences observed over industrial and business centers may not be similar to that which might be anticipated over an undeveloped flat area (U. S. Weather Bureau, 1955); nocturnal surface inversions over these centers may be rare rather than the rule

(DeMarrais, 1961). In contrast with the flat areas, the undeveloped hilly areas do not heat as readily and at night cool off more rapidly (Geiger, 1957).

Local wind effects may also be experienced. The gently rolling terrain of the eastern half of the metropolitan area has practically negligible effects on the winds, but the hills and valleys of the western part may turn or channel the winds. Also, drainage winds along the hillsides may bring cold air down into the valleys and the lowlands and thereby alter the horizontal temperature gradient.

Meteorological Stations in Tulsa

The meteorological data used in this report were collected at two stations, the U. S. Weather Bureau Airport Station (WBAS) and the Tulsa Meteorological Tower Station (TMT) at the University of Tulsa. Both stations are in the eastern suburbs of Tulsa and a considerable distance from the hills which might have a noticeable effect on the observed meteorological parameters. The WBAS takes the standard weather observations and from these the wind, sunshine, cloudiness and precipitation records are used. At the TMT site a vertical temperature difference measuring system and Aerovane unit were installed on a 226-foot radio tower. Temperature differences between heights of 26, 91, and 215 feet and wind measurements at 215 feet were obtained with the tower instruments. The Tulsa City-County Health Department maintained the instruments at the University site and performed the preliminary steps in reducing the data.

Major portions of the records from the TMT site were missed during January, February and July 1959 and after January 1960. It was therefore decided that the analyses would cover the data collected from December 1957 to November 1959.

Pertinent Climatology

General

A recent study (Korshover, 1960) indicates that prolonged light anticyclonic flow or long-duration air stagnation over Tulsa occurs infrequently. Only two cases of light surface winds lasting four days or more occurred during the 1936-1956 period. It thus appears that extended periods of high concentrations of pollutants as a result of meteorological conditions would rarely occur.

On the other hand, occurrences of short-duration air stagnation are frequent. Stagnation, however, is not the only phenomenon conducive to poor air quality in the Tulsa area. Strong winds which provide relatively large volumes of air for mixing with effluents will usually allow relatively little atmospheric dilution after the initial mixing. These winds may therefore occasionally carry some of the local industries' noxious concentrations of effluents, e.g., odors, into residential and business districts. Attention is therefore given to the strong wind as well as to the light wind situation.

Winds

Surface observations at the airport (WBAS). Rather than use wind roses based on only the two years of data collected in this study the more reliable 5-year wind roses presented in the initial report are evaluated; these wind roses are in the appendix. *

* During the period used as a basis for the wind roses, 1949-1953, the WBAS anemometer was at at height of 60 feet; during the period covered by this study it was at 39 feet.

On an annual basis there is bimodal distribution of wind direction frequencies. When the wind is not from the more frequent direction, the south, it is usually from the north. The bimodal distribution is quite obvious in all but the summer months. The 1957-1958 and 1958-1959 winter data (cf. Table A1) show that north winds may occasionally be more frequent than those from the opposite direction. One important feature on the wind roses which should not be overlooked is the relative infrequency of calm conditions.

In order to determine if there were any seasonal and diurnal variations in the flow pattern the frequencies of each of 16 directions for each hour of every month were determined. For the micrometeorologist who might be interested in details the results for alternate hours are presented in Table A1 in the Appendix. However, not all these data need be examined to discover the noteworthy variations. Consideration of Table 1 in which

Table 1. MOST FREQUENTLY OBSERVED WIND DIRECTION, WBAS, DEC. 1957 TO NOV. 1959

Month	Hour of Day											
	0	2	4	6	8	10	12	14	16	18	20	22
Dec.	S	SSE	SSE	SSE	S	S	S	S	S	S	SSE	SSE
Jan.	SSE	SSE	SSE	N	S	S	S	S	S	NNE	SSE	S
Feb.	N	NNE	NNE	N	N	S	S	NNE	NNE	N	NNE	N
March	N	N	SSE	N	SSE	N	N	N	N	N	N	N
April	S	S	S	S	N	S	S	SW	S	N	S	S
May	S	SSE	SSE	SSE	S	S	S	SSE	S	SSE	S	SSE
June	SSE	S	SSE	SSE	SSE	S	S	S	S	SSE	SSE	S
July	S	S	SSE	S	S	SSW	SSW	S	S	S	SSE	SSE
Aug.	SSE	S	SSE	SSE	SSE	SSW	S	SSW	S	SSE	SSE	SSE
Sept.	SSE	SSE	SSE	SSE	SSE	S	S	S	S	SSE	SSE	SSE
Oct.	SSE	S	SSE	SSE	SSE	SSW	S	SSW	S	SSE	SSE	SSE
Nov.	SSE	SSE	SSE	SSE	SSE	SSE	S	S	S	S	SSE	S

Anemometer height, 39 feet.

the most frequently observed wind directions for alternate hours for each month are presented is sufficient for this purpose. The prevalence of winds with a southerly component, regardless of time of day for nine months of the year and the high frequency of northerly winds in late winter are evident. Not so apparent is the slight diurnal shift when southerly winds prevail. At night the winds usually blow from the south-southeast while during the day they are from the south or southwest. No diurnal variation is detected when northerly winds prevail. Also the hour-to-hour records show that no turning from north to south or vice-versa on a regular diurnal basis is observed.

Not only less frequent, those winds which blow from the east and the west are usually lighter than northerly or southerly winds (cf. Figure A1). To detect any diurnal or seasonal variation in wind speed, average hourly values were determined for alternate hours for each month and are shown in Table 2. As is usual

Table 2. TULSA WBAS AVERAGE HOURLY WIND SPEEDS (MPH) DEC. 1957-NOV. 1959

Month	Hour of Day											
	0	2	4	6	8	10	12	14	16	18	20	22
Dec.	7.2	7.3	7.6	7.2	7.3	9.1	9.5	10.3	9.2	7.5	7.2	8.0
Jan.	8.3	7.9	6.9	7.4	7.9	8.9	11.3	11.3	11.3	8.9	8.4	8.6
Feb.	8.6	9.0	9.3	9.2	8.7	9.4	10.4	10.9	11.4	9.5	9.1	9.4
March	8.4	8.0	8.5	8.4	9.0	11.0	11.2	11.2	10.8	10.5	8.2	8.4
April	8.5	7.9	8.3	8.2	9.4	11.1	11.2	11.7	10.9	10.4	8.3	8.5
May	7.6	6.5	6.0	6.6	8.2	9.8	9.5	10.2	9.5	9.0	6.6	6.9
June	6.3	5.2	6.0	5.6	7.5	8.9	8.7	9.7	9.1	8.8	6.5	6.5
July	6.5	6.5	6.5	5.9	7.9	8.8	9.2	8.9	9.1	8.6	6.0	6.7
Aug.	5.2	4.8	4.8	5.0	6.3	7.2	7.3	7.5	7.7	7.4	5.5	6.0
Sept.	6.9	6.5	6.3	6.6	8.0	9.9	9.8	10.3	9.7	8.9	7.8	7.6
Oct.	6.3	5.7	5.4	5.5	6.6	8.6	9.1	9.2	8.5	6.5	6.3	6.0
Nov.	7.2	6.8	7.8	8.0	8.4	10.2	11.2	10.8	10.5	7.9	7.1	7.4

Anemometer height, 39 feet.

with surface winds, the speeds at Tulsa are higher during daylight hours than at night and are highest in spring and lowest in the summer. The lowest wind speeds during the day are usually experienced just before sunrise and the highest occur in the early afternoon.

Winds observed on the Tulsa Meteorological Tower (TMT). The two years of data obtained at the 215 foot level of the tower indicate that the bimodal distribution of directions observed on the surface at the WBAS is also recorded aloft. However, the frequency of winds from the cardinal points of north and south rather than from sectors is slightly more pronounced at the upper level. As for calms, during only 1 of more than 12,000 hours of observation was an absence of wind movement recorded.

For comparison the tower wind data were reduced in a manner similar to those for surface winds. In the Appendix the frequency of each of the 16 directions for alternate hours of every month except November are listed in Table A2. Table 3 lists the most frequently observed wind directions for alternate hours for each month (excluding November). The latter table over-emphasizes somewhat the prevalence

Table 3. MOST FREQUENTLY OBSERVED WIND DIRECTIONS, 215 FEET (TMT), DEC. 1957 TO NOV. 1959 (EXCLUDING NOV., DEC., 1958, JAN., FEB., JULY, NOV., 1959)

Month	Hour of day											
	0	2	4	6	8	10	12	14	16	18	20	22
Dec.	S	SSW	SSW	SSW	S	SSW	SSW	SSW	S	SSW	SSW	S
Jan.	SSE	SSE	SSE	NW	SSE	N	SSW	S	SSE	SE	SE	SSE
Feb.	NNE	NNE	NNE	NNE	NE	NNE	NNE	N	N	N	N	N
March	N	N	N	N	N	S	N	N	N	N	N	N
April	S	S	S	N	S	S	S	S	S	SSW	S	S
May	S	S	S	S	S	S	S	S	S	S	S	S
June	S	S	S	S	S	S	S	S	S	S	S	S
July	S	S	S	S	S	S	S	S	SSW	S	S	S
Aug.	S	S	S	S	S	S	SSW	SSW	SSW	S	S	S
Sept.	S	S	S	S	S	S	SSW	SSW	S	S	S	S
Oct.	S	S	S	S	S	S	S	S	SSW	S	S	S

of winds from the cardinal directions but does give a true indication of the relative frequency of each mode. In the late winter and early spring northerly winds occur more frequently than winds from the opposite direction but thereafter until the onset of winter southerly winds are much more frequent. In winter, winds from each mode blow with about equal frequency. As to a turning of the wind on a diurnal basis, that which occurs is very slight and is observed from May to October. At that time the southerly winds of the morning occasionally become south-southwesterly in the afternoon and return to southerly after sunset.

Like the surface wind speeds those aloft showed the winds from the modal directions to be stronger than those from the other directions. However, the diurnal variation of speed at 215 feet is just opposite to that observed near the surface. The average hourly wind speeds, as shown in Table 4, are stronger at night than during the day. At all hours during all months the average winds provide good transport. The strongest winds occur in winter and the lightest in summer.

Table 4. AVERAGE WIND SPEED (MPH) 215 FEET (TMT) DEC. 1957–NOV. 1959

Month	Hour of day											
	0	2	4	6	8	10	12	14	16	18	20	22
Dec.	14.3	14.8	14.8	14.3	14.3	11.7	11.8	12.5	12.5	11.6	13.2	14.4
Jan.	13.6	12.5	12.5	12.8	12.9	11.9	12.4	12.8	12.2	12.1	13.5	13.8
Feb.	13.9	13.2	12.7	12.7	11.8	11.1	11.7	12.1	12.1	12.0	13.7	14.5
March	13.3	13.7	13.2	13.3	12.8	12.7	12.8	13.0	13.0	12.6	12.8	13.3
April	13.6	13.8	13.8	13.6	12.7	13.0	13.5	12.4	12.5	13.0	12.6	13.3
May	13.0	13.0	12.4	12.7	10.8	11.9	11.7	12.1	12.3	12.0	11.8	12.7
June	12.4	12.4	12.5	12.4	11.1	11.1	11.2	12.2	11.8	11.6	11.1	11.6
July	12.4	12.2	12.4	12.2	11.4	10.6	10.4	11.5	10.8	11.5	10.9	12.3
Aug.	12.0	11.7	11.9	11.3	9.8	9.9	10.1	9.9	10.8	10.6	11.0	12.2
Sept.	13.0	12.7	12.2	12.5	10.7	11.5	12.4	12.1	12.3	11.8	11.1	13.2
Oct.	12.7	13.5	12.8	12.6	12.2	10.5	10.8	11.1	10.9	10.4	12.5	12.6
Nov.	13.3	12.8	13.4	14.1	13.5	13.1	13.0	13.4	13.3	11.8	12.6	13.7

Short duration air stagnation. The persistence of winds of less than 5 mph would be conducive to air stagnation or the lack of ventilation. The tower winds were therefore analyzed to determine the monthly frequency of light winds of several hours duration. The results in Table 5 show that even short periods of air stagnation were not frequent. Light winds lasting throughout a night occurred about a half-dozen times in the two years and in no case did such light winds persist for 20 hours.

Table 5. AVERAGE MONTHLY FREQUENCY OF PERIODS OF WINDS UNDER 5 MPH, 215 FEET (TMT) DEC. 1957–NOV. 1959

Month	Consecutive hours duration		
	5	10	15
Dec.	2		
Jan.	5	*	
Feb.	2	*	
March	2		
April	1		
May	3	1	
June	1		
July	*		
Aug.	3	1	*
Sept.	*		
Oct.	3		
Nov.			

* = Less than one.

Strong winds. Inasmuch as strong winds may lead to occasions of noxious surface concentrations the tower winds were examined for the frequency of occurrence of high wind speeds. Since the threshold or lowest wind speed which would prevent sufficient dilution, after the initial mixing near the source, would vary with concentration, frequencies for each five mph interval starting as low as 15 mph were determined. The results are shown in Table 6. Winds greater than 15 mph are observed about 20 percent of the time except during August. However, duration as well as frequency of occurrence of high wind speeds are important in this poor diffusion case. The value of 20 mph was therefore arbitrarily accepted as the threshold number in order to obtain some idea of the duration of these situations. Using this value with the tower data it was determined that Tulsa had observed 24-hour periods of "poor diffusion" once or twice a year and all occurrences had been in the spring.

Table 6. FREQUENCY (% OF HOURLY OBSERVATIONS) OF HIGH WIND SPEEDS, 215 FEET (TMT), DEC. 1957–NOV. 1959

Month	Wind Speed (MPH)			
	>15	>20	>25	>30
Dec.	21	6	4	
Jan.	26	7	2	*
Feb.	17	9	1	*
March	18	11	2	
April	22	12	1	
May	20	7	1	
June	15	7	1	
July	23	5	0	
Aug.	10	0	0	
Sept.	21	6	0	
Oct.	17	4	1	
Nov.	24	11	3	*

* = Less than 1%.

Diffusion

Wind records indicative of the relative amount of horizontal diffusion. Detailed analysis of the wind direction records from the tower have provided an indication of the diurnal and seasonal variation of turbulence and consequently the variation in horizontal diffusion. Average hourly wind direction ranges were determined and the values for alternate hours for each month are shown in Table 7. The range and thus the inferred horizontal diffusion are greatest in the summer and least in winter. The ratio of summer to winter average range is about 1.75 to 1. The diurnal variation in range is greater than the seasonal; the averages during the day are approximately twice as great as those at night.

Table 7. AVERAGE WIND DIRECTION RANGE (IN COMPASS DEGREES), 215 FEET (TMT) DEC. 1957 TO OCT. 1959 (EXCLUDING NOV., DEC., 1958, JAN., FEB., FULY, 1959)

Month	Hour of day											
	0	2	4	6	8	10	12	14	16	18	20	22
Dec.	55	52	49	51	60	85	104	102	94	63	48	53
Jan.	42	49	41	45	48	77	86	90	89	54	44	50
Feb.	61	58	57	57	62	83	93	102	85	66	51	50
March	62	59	57	59	70	98	107	111	108	85	71	62
April	68	62	63	63	87	109	122	131	134	104	68	72
May	60	61	58	66	94	112	132	130	111	102	73	66
June	58	55	60	68	106	133	155	148	137	112	72	55
July	70	90	72	94	103	113	148	121	132	107	74	84
Aug.	58	57	60	57	96	104	138	156	126	99	68	66
Sept.	68	66	61	61	87	114	137	129	125	88	68	65
Oct.	52	51	45	64	72	100	120	135	119	70	53	55

Although a direct quantitative comparison to diffusion cannot be made, one can use Table 7 to obtain an indication of the variation of the horizontal spread of a plume. The most noteworthy feature of the average wind direction ranges is that all are larger than 40°, indicating that horizontal diffusion was good at all times.

Vertical temperature differences as indicators of diffusion. Thermal stability evaluations based on vertical temperature difference observations may be used as an indicator of the vertical diffusive characteristics of the atmosphere. When the temperature decrease between 25 and 215 feet is great enough so that the layer is thermally unstable, vertical diffusion is enhanced. With a temperature decrease of 1.0°F or less between 25 and 215 feet there may be some vertical diffusion but not as much as there is in an unstable atmosphere. Increasing temperatures with height are indicative of a stable atmosphere and are accompanied by very little vertical diffusion.

The temperature differences presented in Tables 8 and 9 differ somewhat from most of the previously published data (e.g., Weather Bureau, 1955). In the past, nearly all vertical temperature differences were obtained in flat, rural areas and it appears that not all of the generalizations formulated for those areas can be applied to Tulsa. Inasmuch as the data in the present tables represent relatively short periods of record, weather anomalies may have had an effect on the observed temperature differences. Table A3 in the Appendix lists the principal departures from normal and weather abnormalities that were recorded in each month of the period of investigation.

Table 8. AVERAGE TEMPERATURE LAPSE RATES BETWEEN 26 AND 91 FEET (TMT) DEC. 1957–NOV. 1959 (EXCLUDING JAN. AND FEB. 1959)

Month	Hour of day											
	0	2	4	6	8	10	12	14	16	18	20	22
Dec.	+0.1	+0.1	-0.1	-0.1	-0.1	-0.7	-1.2	-1.2	-0.9	-0.1	+0.1	+0.1
Jan.	0.0	0.0	-0.1	0.0	-0.2	-0.8	-1.3	-1.3	-1.0	-0.3	0.0	0.0
Feb.	-0.5	-0.4	-0.5	-0.4	-0.6	-1.1	-1.5	-1.4	-1.2	-0.7	-0.4	-0.4
March	-0.2	-0.2	-0.2	-0.2	-0.6	-1.2	-1.5	-1.6	-1.3	-0.7	-0.3	-0.2
April	-0.2	-0.2	-0.3	-0.3	-1.0	-1.5	-1.8	-1.8	-1.6	-0.9	-0.4	-0.2
May	-0.1	-0.2	-0.2	-0.3	-1.1	-1.4	-1.6	-1.8	-1.4	-0.8	-0.3	-0.1
June	-0.1	-0.1	-0.2	-0.4	-1.2	-1.5	-1.8	-1.8	-1.6	-1.1	-0.6	-0.3
July	-0.8	-0.8	-0.9	-0.9	-1.5	-2.1	-2.5	-2.5	-2.2	-1.4	-0.7	-0.8
Aug.	-0.6	-0.6	-0.7	-0.8	-1.7	-2.6	-3.2	-3.5	-3.0	-1.4	-1.0	-0.7
Sept.	-0.3	-0.2	-0.3	-0.4	-0.9	-1.9	-2.5	-2.7	-2.4	-1.0	-0.6	-0.4
Oct.	-0.1	-0.2	-0.2	-0.2	-0.1	-1.7	-2.4	-2.5	-2.0	-0.5	-0.1	0.0
Nov.	-0.1	-0.1	-0.2	-0.2	-0.2	-1.1	-2.3	-2.3	-1.8	-0.4	+0.1	0.0

Adiabatic lapse rate (26 to 91 ft.) = -0.4F

Table 8 listing the bihourly, monthly average temperature differences between 25 and 91 feet shows that large temperature decreases with height or superadiabatic conditions prevailed during the day. Such observations are in accord with the generalizations for nonurban areas. However, at night a fairly wide range of conditions were recorded and no general rule could be determined. The nocturnal observations of February, July, and August showed that superadiabatic conditions prevailed. Those of March, April, May, June, September and October showed average conditions between adiabatic and isothermal. The nighttime observations of November, December and January were near isothermal. On the basis of this analysis the first group of months would be thought of as affording good vertical diffusion at night, the second group as providing slightly poorer conditions and the final as marked by relatively little vertical diffusion.

Table 9. AVERAGE TEMPERATURE LAPSE RATES BETWEEN 91 AND 215 FEET (TMT) DEC. 1957–NOV. 1959 (EXCLUDING JAN. AND FEB. 1959)

Month	Hour of day											
	0	2	4	6	8	10	12	14	16	18	20	22
Dec.	+0.7	+0.9	+1.0	+0.8	+0.4	-1.0	-1.2	-1.3	-1.1	-0.5	+0.3	+0.4
Jan.	+0.3	+0.4	+0.2	+0.4	-0.3	-1.0	-1.3	-1.2	-1.1	-0.8	+0.1	+0.1
Feb.	-0.4	-0.4	-0.2	-0.4	-0.5	-1.1	-1.3	-1.3	-1.2	-1.0	-0.7	-0.4
March	-0.3	-0.2	-0.3	-0.3	-0.3	-1.3	-1.4	-1.4	-1.4	-1.1	-0.6	-0.4
April	-0.3	+0.1	+0.1	0.0	-1.1	-1.6	-1.6	-1.7	-1.5	-1.3	-0.8	-0.6
May	-0.6	-0.6	-0.5	-0.5	-1.7	-2.0	-2.0	-2.0	-2.0	-1.9	-1.5	-1.0
June	-0.9	-0.5	-0.4	-0.7	-1.9	-2.2	-2.1	-2.3	-2.1	-1.9	-1.5	-1.1
July	-0.7	-0.4	-0.5	-0.8	-1.7	-2.0	-2.0	-1.9	-1.7	-1.4	-1.2	-1.0
Aug.	-0.2	0.0	+0.2	+0.2	-1.6	-2.0	-1.6	-1.8	-1.4	-1.0	-1.2	-0.4
Sept.	+0.2	+0.4	+0.2	+0.1	-1.0	-1.3	-1.3	-1.6	-1.3	-0.6	-0.3	+0.1
Oct.	+0.7	+1.0	+0.7	+0.7	-0.2	-1.1	-1.2	-1.4	-1.2	-0.5	+0.	-0.6
Nov.	+0.7	+0.8	+1.1	+1.3	+0.5	-1.2	-1.4	-1.4	-1.2	-0.1	+0.	0.6

Adiabatic lapse rate (91 to 215 ft.) = -0.7F

Table 9 showing the temperature differences between 91 and 215 feet indicates that the upper layer was similar to the lower one during the day, i.e., superadiabatic conditions prevailed. Nocturnal inversions occurred much more frequently in this layer than in that between 25 and 91 feet and are quite routine from September through January. In contrast to the lower layer no month was marked by averages indicating that superadiabatic conditions prevailed during the night.

Sunshine and cloudiness as indicators of vertical diffusion. The percentage of possible sunshine and the state of the sky (percentage of cloudiness) are less direct indicators of the amount of vertical diffusion. On days when the percentage of sunshine is high there will be a considerable amount of vertical diffusion as a result of the convection caused by surface heating. Since clouds cut off the rays of the sun and thus reduce surface heating their presence or absence may be used as a rough index of the relative amount of diffusion. Cloud observations at night may also be used. A cloudless nocturnal sky would allow terrestrial radiation to escape to the atmosphere and enhance the development of stable conditions, whereas a cloudy sky would hinder any such escape and, if accompanied by strong winds, maintain a near adiabatic temperature difference (Sutton, 1951).

Table 10 shows the percent of sunshine and the number of clear days (80% sunshine or more) observed at the WBAS during each month of the two years of the study. The indication is that there were considerable variations from month to month and year to year except during October, November, and December when at least half the days of the month were relatively sunny and clear. No month was marked by cloudless conditions, but only February appeared to be a month with a relatively small amount of sunshine. It would have been useful to analyze sunshine intensity data also, but such measurements were not available in Tulsa.

Table 10. SUNSHINE DATA, WBAS, NOVEMBER 1957–DECEMBER 1959

	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov
	Percent of possible sunshine											
1957-8	58	67	42	30	46	56	82	71	63	47	62	65
1958-9	60	49	36	64	60	36	49	56	71	70	62	67
	Number of clear days (80% sunshine or more)											
1957-8	12	18	7	5	4	13	19	16	13	6	14	17
1958-9	18	10	5	16	11	4	7	8	17	16	16	17

The observed amount of cloudiness as obtained from the WBAS during the study is seen in Table 11. During the day there appeared to be no regular seasonal variation in the amount of cloudiness. However, the nighttime observations indicated a significant consistency; the months of June through November were marked by relatively small amounts of cloudiness. In all but one month the average cloudiness at night is less than during the day.

Table 11. CLOUDINESS (TENTHS), WBAS, DECEMBER 1957–NOVEMBER 1959

Month	1957–1958		1958–1959	
	Daytime	Nighttime	Daytime	Nighttime
Dec.	5.2	4.3	5.2	5.3
Jan.	6.1	4.3	6.6	5.8
Feb.	7.6	5.4	6.6	6.1
March	7.9	7.2	4.4	3.4
April	6.6	6.3	6.5	5.2
May	6.3	5.0	7.2	6.0
June	4.6	3.2	6.0	2.9
July	5.6	3.2	6.3	4.3
Aug.	5.0	3.5	4.0	1.7
Sept.	6.4	5.0	4.4	3.4
Oct.	5.8	3.6	4.3	4.0
Nov.	4.8	4.1	4.4	4.1

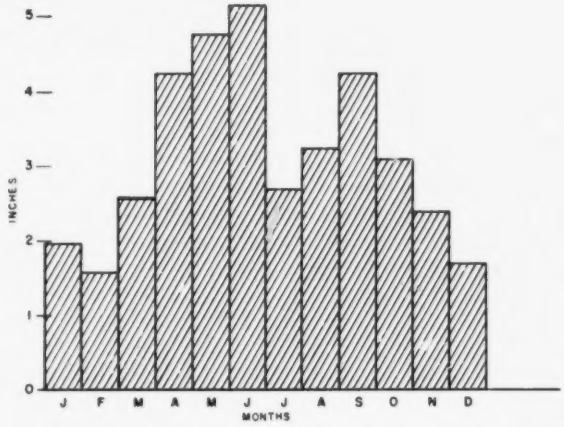


Figure 4. NORMAL MONTHLY RAINFALL, TULSA (water equivalent of frozen forms used)

Precipitation

Precipitation, when it acts as a cleansing agent of the atmosphere, is important in air pollution. The data collected during the short period of this study were very sparse; thus, normals determined at the WBAS are used as the basis for inferring the washout effects on the air quality of Tulsa.

Figure 4 shows the monthly normal precipitation. The warmer part of the year has the heaviest rainfall. On a daily basis a heavy precipitation fall of 0.50 inch or more may occur in any month of the year. The fall and winter are the seasons of lightest amounts of precipitation. In terms of washout the greatest potential exists during the warm months and the least during the fall: the light precipitation of winter is presumed to be more effective than that of all for some of it is in the form of snowflakes, which are more effective collectors of particulates than are water droplets.

Discussion

General

Based on the observed meteorological parameters it appears that Tulsa is not particularly susceptible to serious air pollution problems of long duration. Prolonged air stagnation would be exceptionally rare and even short periods of poor air quality should be infrequent. The frequency of relatively high wind speeds which provide good transport of effluents and the almost total absence of calm conditions demonstrate that the ventilating property of the local atmosphere is excellent. Diffusion in the vicinity of Tulsa, as indicated by wind direction ranges and thermal stability, is also excellent; i.e., effluents are spread over wide arcs in the horizontal and vertical. There are seasonal and diurnal variations in the indicated amounts of vertical and horizontal diffusion, but hardly ever will the horizontal spread be small and only occasionally (during periods of inversions on clear nights when light winds or calm conditions are observed) will the vertical diffusion be very small. Precipitation, particularly the heavy rainfalls which are experienced, will wash out the local atmosphere.

Of all the observed meteorological parameters, that which can be most usefully employed in land development planning is the wind direction frequency. Effluents emitted into the atmosphere over Tulsa will most frequently be transported to the north or south. Thus, land

development planners might anticipate which areas would have relatively clean air and plan accordingly.

The western part of the metropolitan region may at times experience local wind and temperature conditions which would affect air quality. The areas to the north and east of industrial sites 1 and 2 on Figure 1 may have short periods of poor air quality because of topography and local meteorological conditions. The air transported by the prevailing and channelled winds reaches the area after having passed over the industrial complexes. The blocking hills and highlands of the area in combination with the winds entrap airborne residues from industry. The poorest conditions occur in early morning and early evening, when fumigation conditions are observed, i.e., large concentrations of effluents are detected at the surface for short periods.

Diffusion

The current state of the art of predicting diffusive conditions in the atmosphere of urban areas is not advanced to the point where it is precise, and the data included in this report are not extensive enough to permit an inference as to the relative concentrations that would be expected under all conditions. However, crude estimates or first approximations of concentrations of effluents from the high stacks of industry may be obtained using formulae (Sutton, 1953) that usually have been found to be accurate within a factor of five. Leavitt (1960) recently designed a method for making these approximations using Sutton's formulae and observed wind roses, and has applied the method to Tulsa. But to make a rapid estimate one needs only Figures 5 and 6; the former indicates the worst effect or maximum relative concentration (roughly a 3-minute average) that is likely to occur, and the latter the place where it will occur. To use Figure 5, one only needs the stack height and wind speed* at stack height, e.g., using a typical Tulsa wind speed of 15 mph and a stack height of approximately 246 feet one could expect a dilution factor of 6.3×10^{-6} at the ground level point of maximum concentration. Figure 6 shows that with a 15 mph wind during the day and a 246-foot stack one would anticipate the maximum ground concentration at 1/3 of a mile downwind (or during a cloudy night, 1 mile downwind).

The tower data in the foregoing sections may be used with Figures 5 and 6 in planning and design but when an air quality problem exists the observed wind speed and direction at stack height should be used.

Diagrams showing isolines of concentrations based on Sutton's formulae would be more convenient references than Figures 5 and 6 and would give a two dimensional view of the relative spread of effluents but the number of these diagrams even for only typical cases would be very large. This presentation is therefore restricted to three cases which are based on some of the most frequently observed conditions. Figure 7 shows the ground concentrations which might be anticipated during daylight hours with 16 mph winds. The basic assumption in this case is that the vertical and horizontal diffusion coefficients are equal. Figure 8 shows the predicted ground concentrations for a clear night with an 11 mph wind. In this case the assumptions are that the diffusion is less than in the former case and the horizontal and vertical diffusion coefficients are equal. Figure 9 shows ground concentrations for the cloudy night with winds near 7 mph. Here the arbitrary assumptions are that the horizontal diffusion coefficient is four times as great as the vertical and the latter is about half the value it was in the clear night case

* An estimated wind speed may be used.

ACKNOWLEDGMENTS

Contributions to this report have been made by many members of the Meteorology Section. In particular, I would like to acknowledge the assistance given by Mr. Francis Pooler, Jr. and Mr. Edward Burt, who critically reviewed the text and made appropriate suggestions. Thanks are also due to Mrs. Ruth Umfleet for patiently and expeditiously taking care of all the details of getting the report through several clearances and revisions.

Figure 3, Courtesy of Tulsa Metropolitan Area Planning Commission.

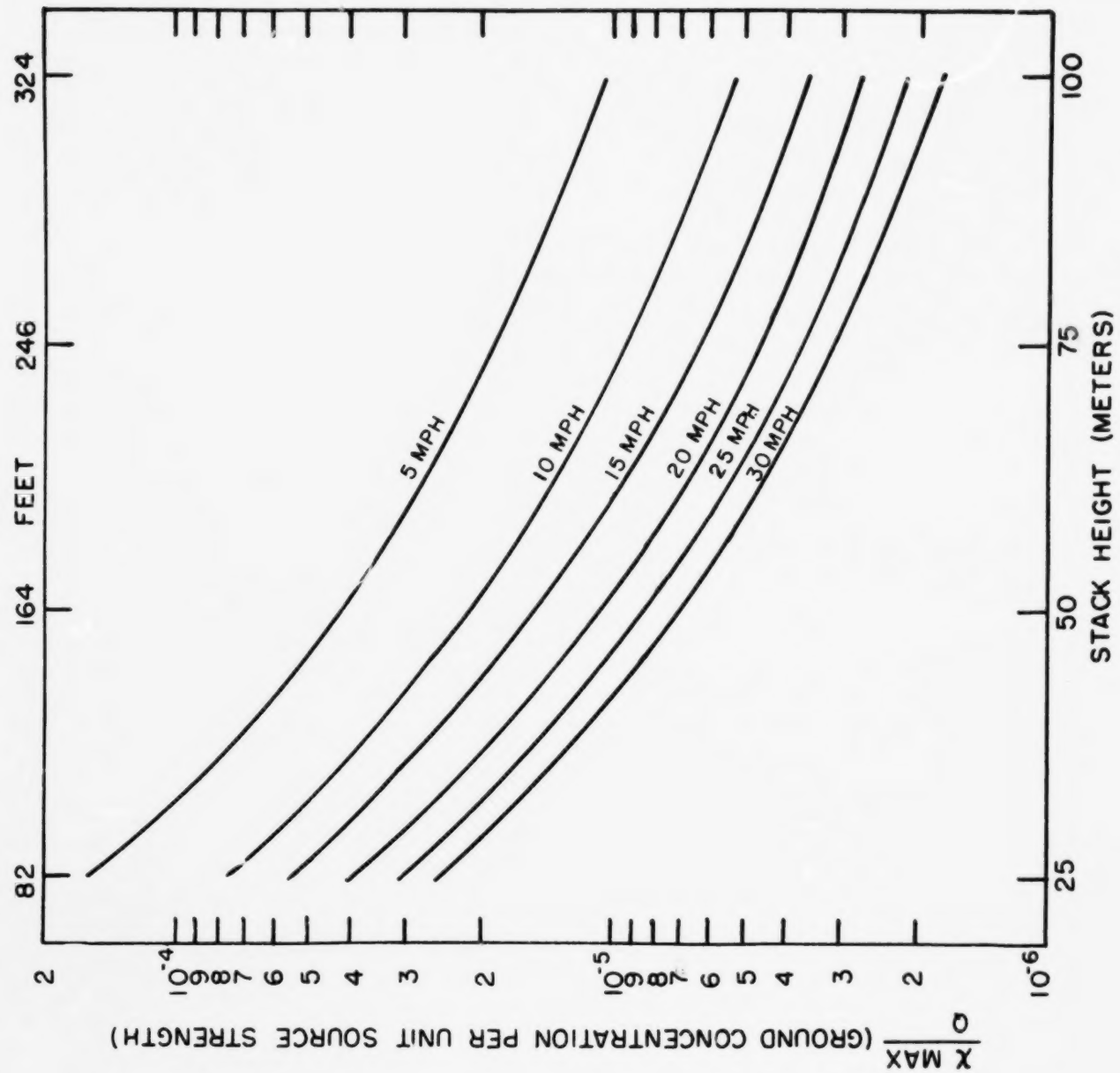


Figure 5. MAXIMUM GROUND CONCENTRATIONS AT A RECEPTOR DISTANCE TO BE DETERMINED FROM FIGURE 6 FOR VARIOUS STACK HEIGHTS AND WIND SPEEDS, CONTINUOUS POINT SOURCE (after Sutton)

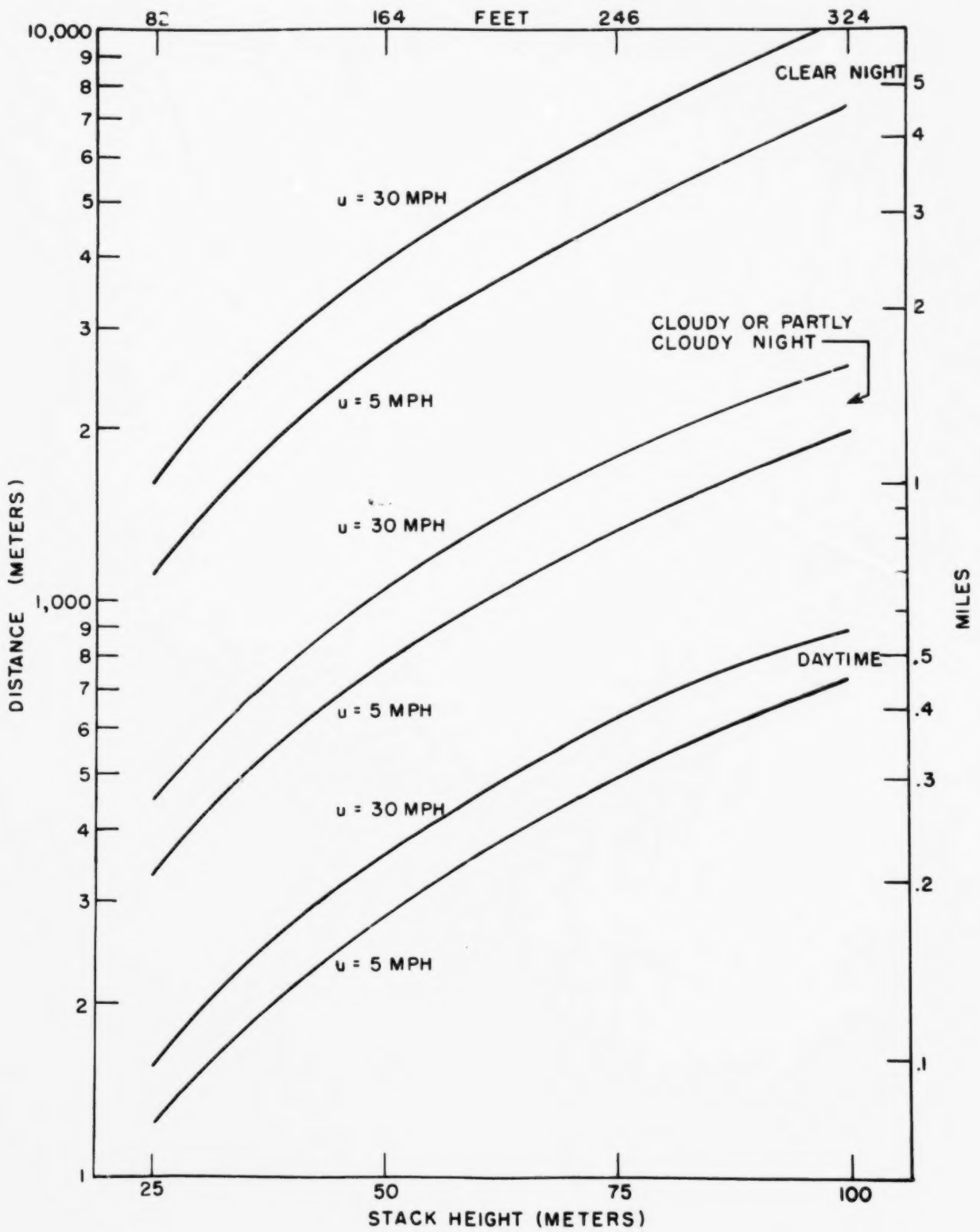


Figure 6. DISTANCE TO $\chi_{(MAX)}$ ELEVATED CONTINUOUS POINT SOURCE (after Sutton)

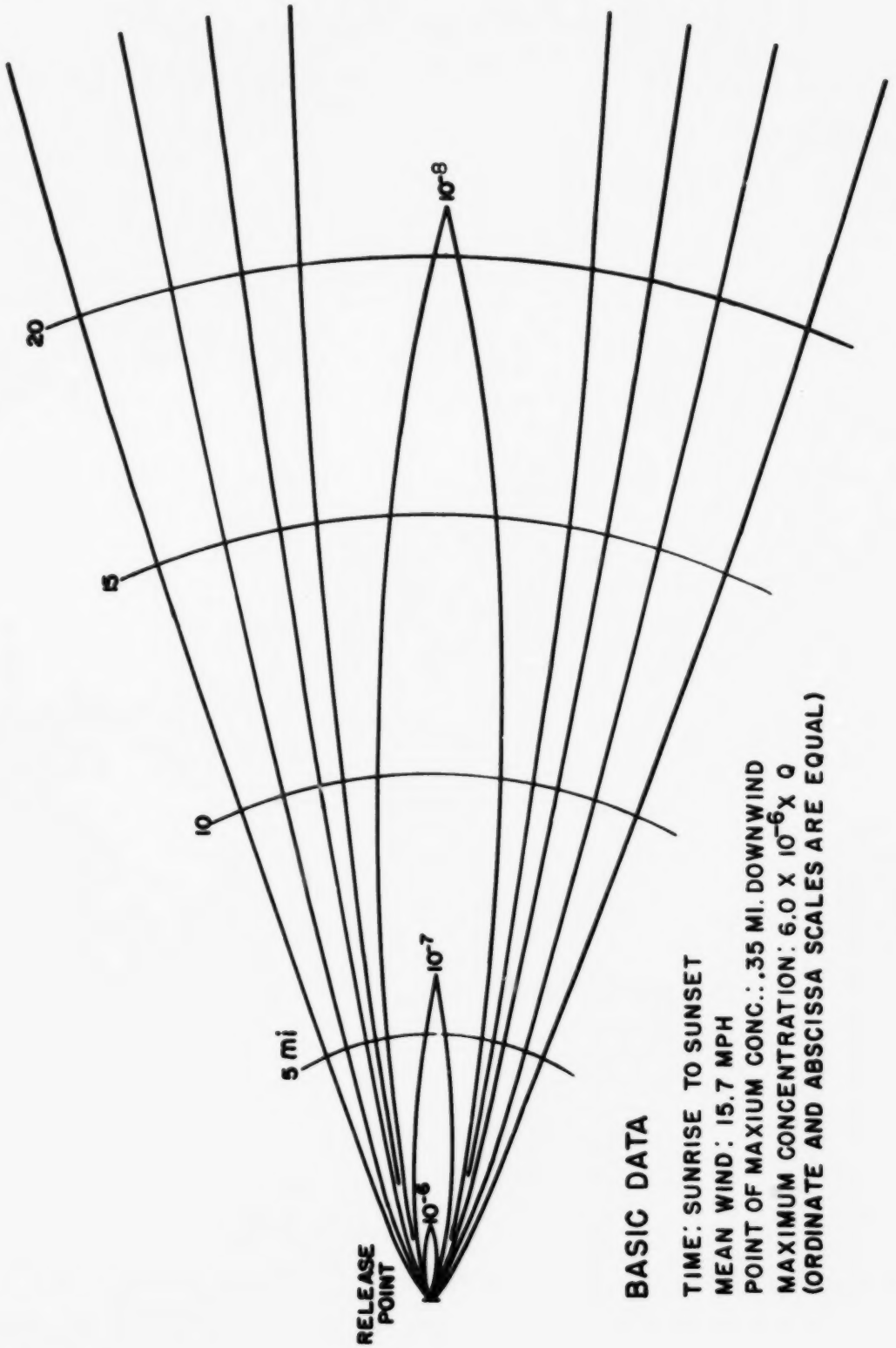
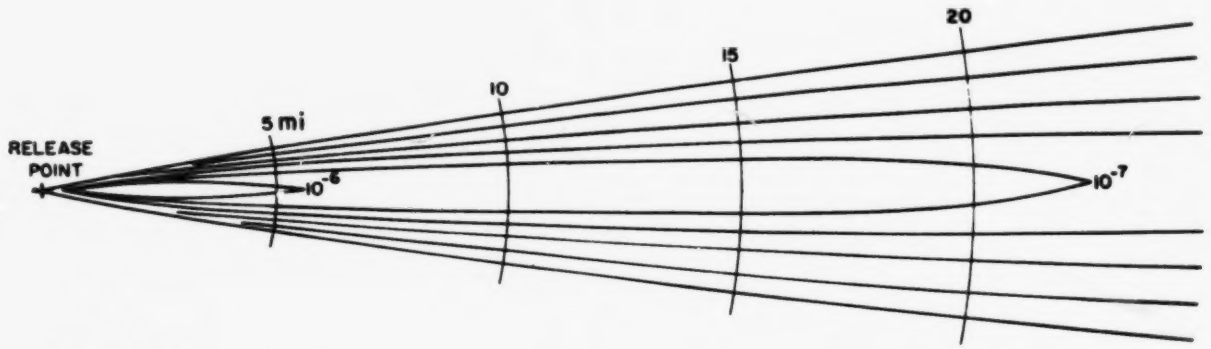


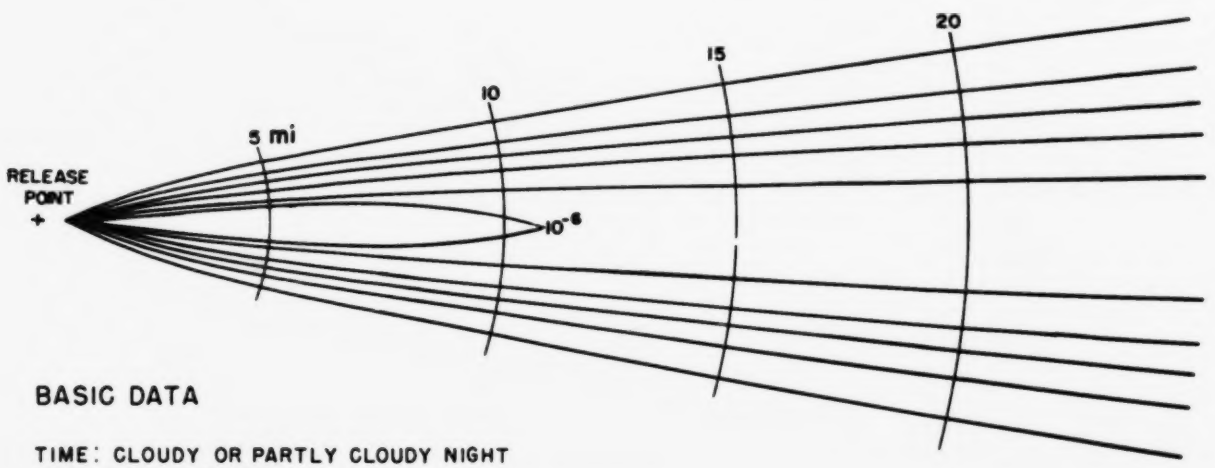
Figure 7. RELATIVE SURFACE CONCENTRATION FROM A CONTINUOUSLY EMITTING POINT SOURCE 75m ABOVE THE SURFACE



BASIC DATA

TIME: CLEAR NIGHT
MEAN WIND: 11.2 MPH
POINT OF MAXIMUM CONCENTRATION: .98 MI. DOWNWIND
MAXIMUM CONCENTRATION: $8.4 \times 10^{-6} \times Q$
(ORDINATE AND ABSCISSA SCALES ARE EQUAL)

Figure 8. RELATIVE SURFACE CONCENTRATION FROM A CONTINUOUSLY EMITTING POINT SOURCE 75m ABOVE THE SURFACE



BASIC DATA

TIME: CLOUDY OR PARTLY CLOUDY NIGHT
MEAN WIND: 6.7 MPH
POINT OF MAXIMUM CONCENTRATION = 3.12 MI. DOWNWIND
MAXIMUM CONCENTRATION = $3.5 \times 10^{-6} \times Q$
(ORDINATE AND ABSCISSA SCALES ARE EQUAL)

Figure 9. RELATIVE SURFACE CONCENTRATION FROM A CONTINUOUSLY EMITTING POINT SOURCE 75m ABOVE THE SURFACE

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APPENDIX

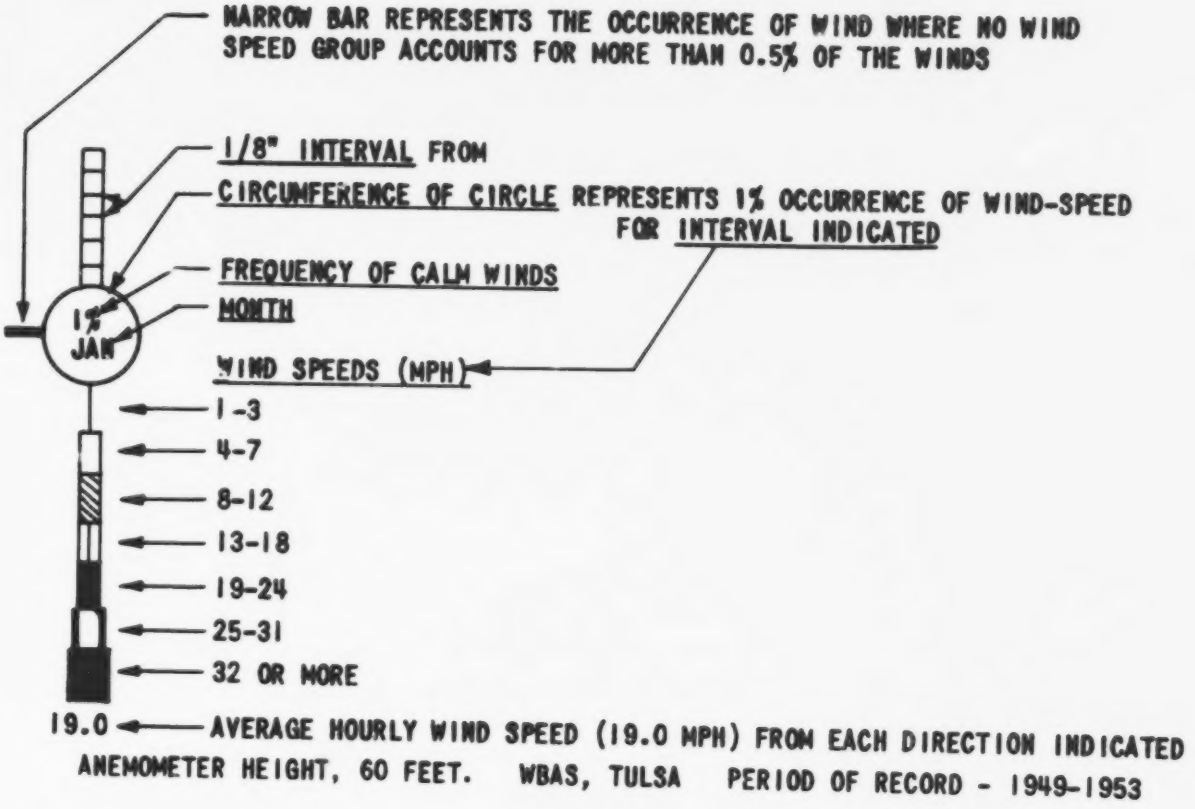
NARROW BAR REPRESENTS THE OCCURRENCE OF WIND WHERE NO WIND SPEED GROUP ACCOUNTS FOR MORE THAN 0.5% OF THE WINDS
1/8" INTERVAL FROM
CIRCUMFERENCE OF CIRCLE REPRESENTS 1% OCCURRENCE OF WIND-SPEED FOR INTERVAL INDICATED
FREQUENCY OF CALM WINDS
MONTH
1%
JAN
WIND SPEEDS (MPH)
1-3
4-7
8-12
13-18
19-24
25-31
32 OR MORE
19.0
AVERAGE HOURLY WIND SPEED (19.0 MPH) FROM EACH DIRECTION INDICATED
ANEMOMETER HEIGHT, 60 FEET. WBAS, TULSA PERIOD OF RECORD - 1949-1953

Figure A1-a. KEY TO SURFACE WIND ROSES

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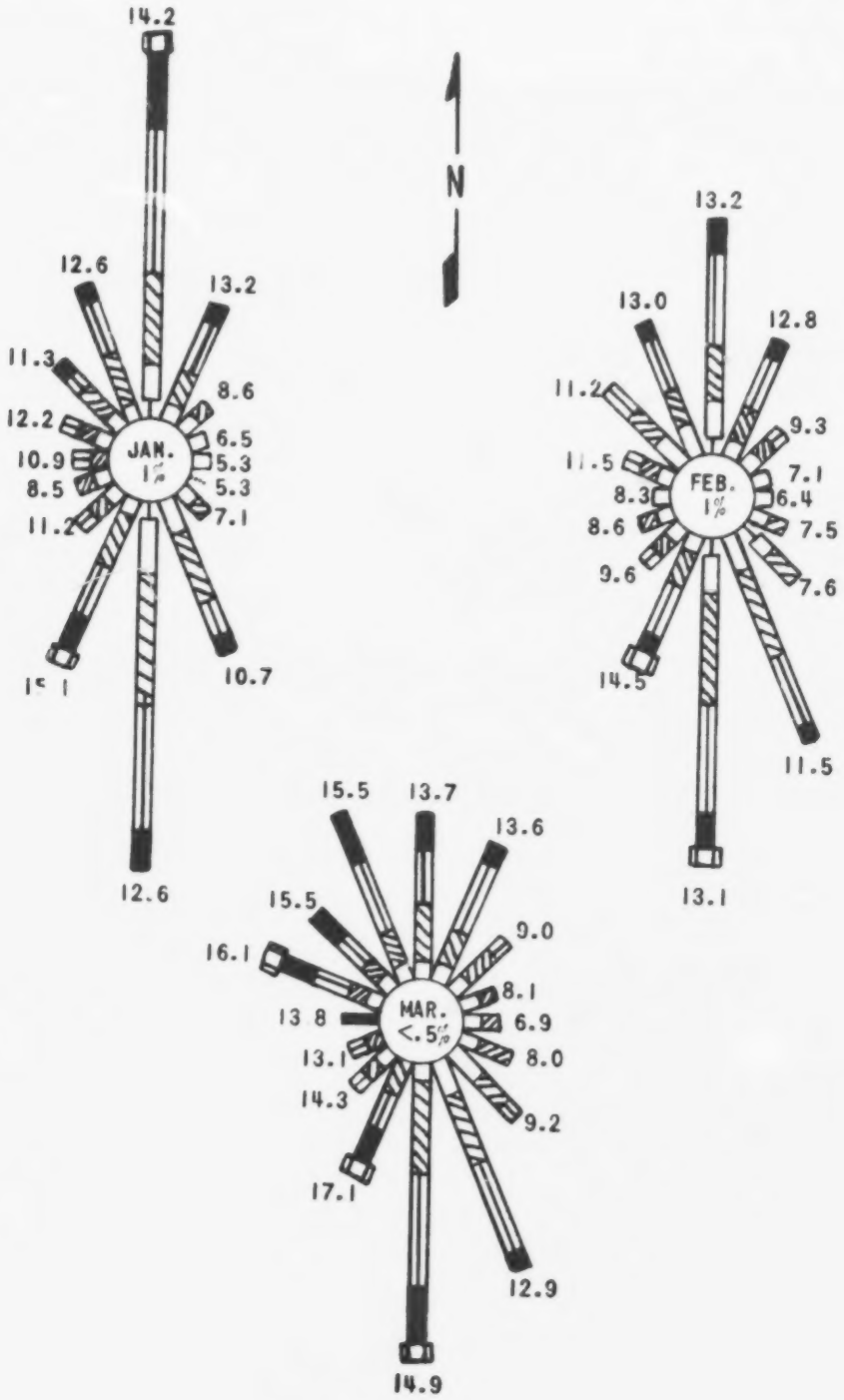

Figure A1-b. TULSA MONTHLY SURFACE WIND ROSES

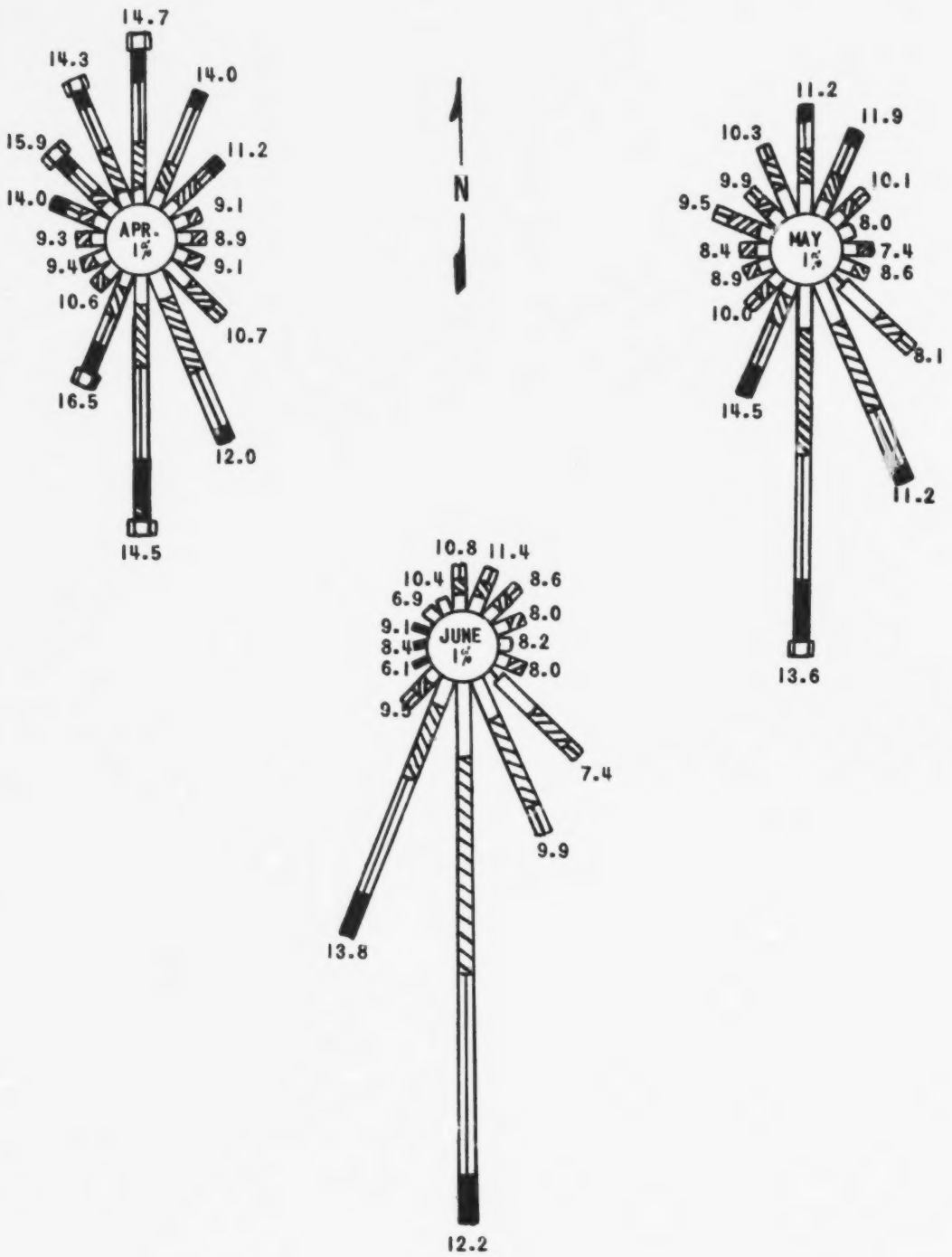

Figure A1-c. TULSA MONTHLY SURFACE WIND ROSES

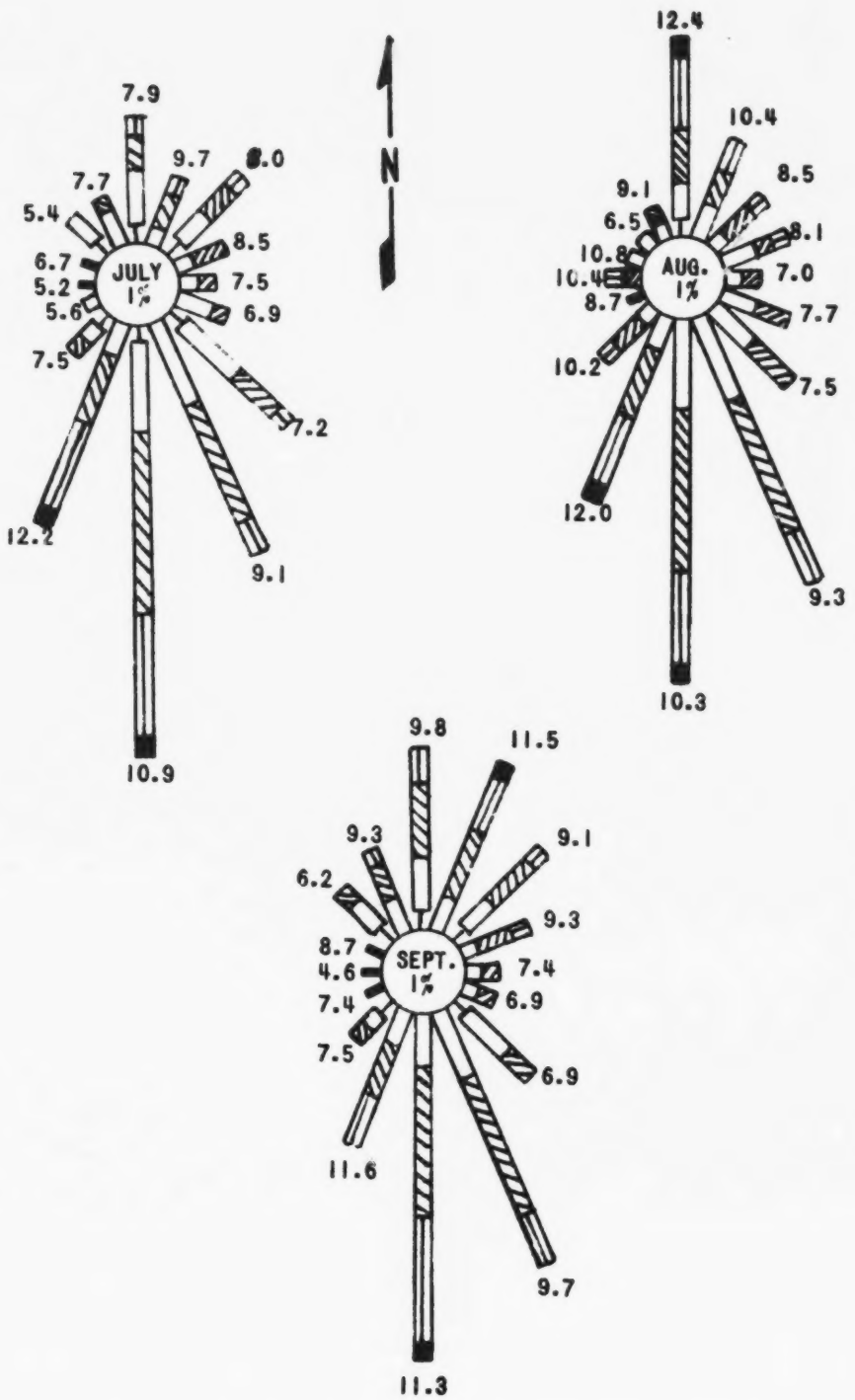

Figure A1-d. TULSA MONTHLY SURFACE WIND ROSES

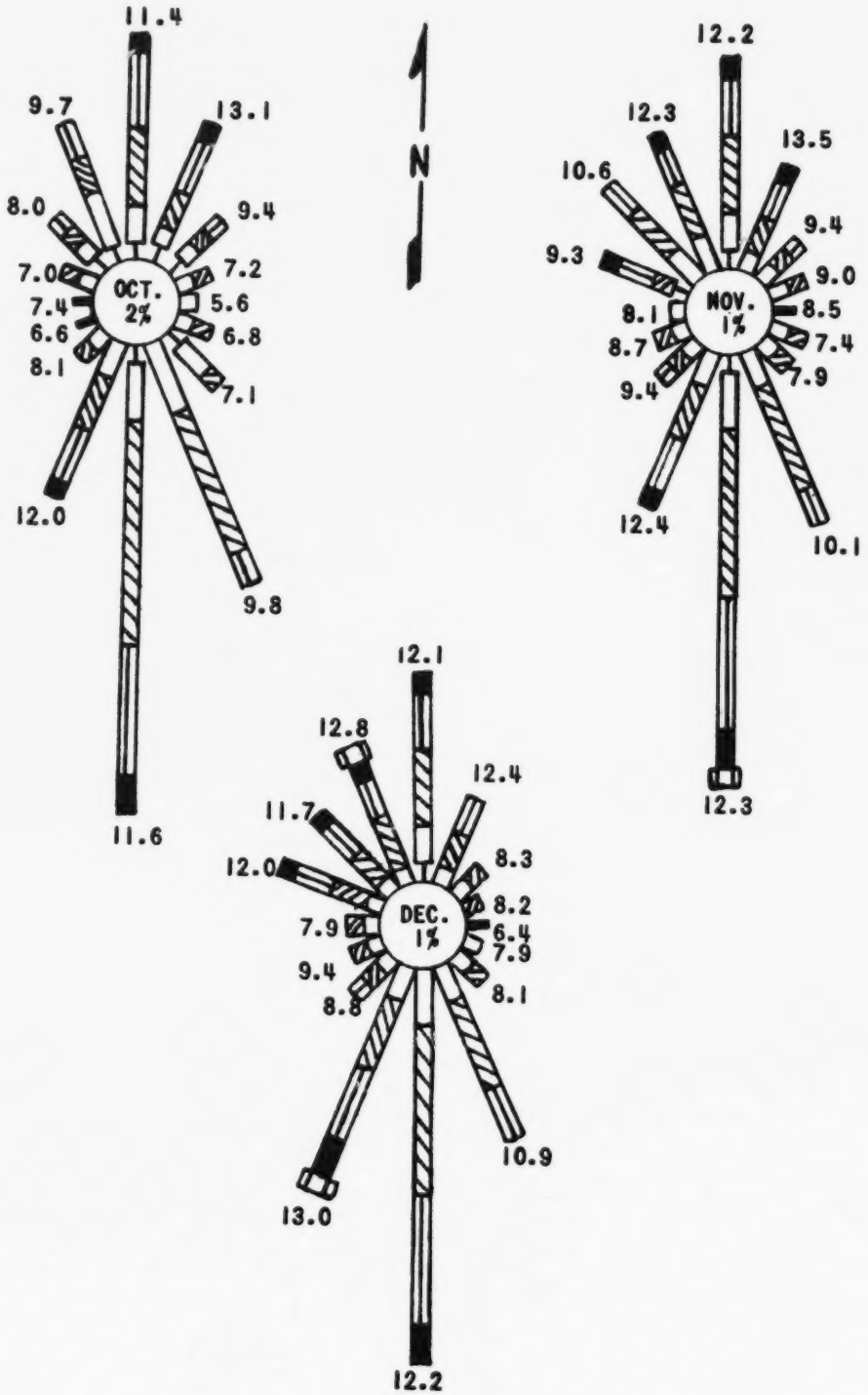

Figure A1-e. TULSA MONTHLY SURFACE WIND ROSES

Table A1-a. HOURLY FREQUENCY OF WIND DIRECTION, WBAS, TULSA (Anemometer Height = 39 feet)

DECEMBER 1957-1958

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	5	7	7	8	5	3	6	10	6	4	4	4
NNE	7	6	6	6	6	7	6	7	3	8	7	6
NE	2	1	1	2	2	3	3	0	6	4	3	4
ENE	0	0	0	0	0	1	0	2	0	0	0	0
E	0	0	0	0	0	0	1	0	1	0	0	0
ESE	0	0	0	0	0	0	1	0	1	0	0	0
SE	1	3	3	5	4	1	1	3	4	5	4	1
SSE	11	15	11	13	11	9	4	4	7	5	12	13
S	15	10	10	6	12	10	12	14	11	13	11	7
SSW	2	3	4	6	1	3	6	6	5	5	3	5
SW	2	1	1	1	0	4	4	1	2	1	2	2
WSW	0	1	0	0	0	0	1	3	1	2	2	1
W	2	0	2	2	3	1	1	2	5	3	1	2
WNW	2	2	3	1	4	2	3	1	1	3	3	3
NW	3	3	4	3	3	5	5	4	3	0	0	4
NNW	2	4	4	4	6	7	4	2	3	2	3	3
CALM	8	6	6	5	5	5	5	3	4	7	7	7

JANUARY 1958-1959

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	9	10	8	10	8	10	12	11	10	6	7	6
NNE	3	4	3	2	3	6	5	8	6	9	7	8
NE	2	0	0	0	1	0	2	2	2	2	1	0
ENE	1	1	0	0	0	0	0	0	1	1	1	1
E	0	2	0	1	0	0	0	1	0	0	0	1
ESE	0	0	1	1	1	0	2	0	2	5	3	3
SE	3	3	5	6	4	4	2	4	2	7	6	3
SSE	12	11	8	5	6	8	3	6	6	7	11	9
S	6	6	7	9	14	10	15	12	15	8	10	10
SSW	4	5	3	4	3	3	6	4	4	1	0	2
SW	2	1	1	2	2	2	3	2	0	0	0	0
WSW	1	2	3	2	0	1	0	1	0	0	0	0
W	3	0	0	0	1	1	0	1	0	1	1	0
WNW	2	2	1	1	0	1	2	1	3	2	3	3
NW	2	5	3	4	6	6	4	4	3	4	4	2
NNW	7	3	8	6	8	3	5	4	6	6	4	8
CALM	5	7	11	9	5	7	1	1	2	3	4	6

FEBRUARY 1958-1959

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	12	9	9	8	9	3	5	4	4	8	6	9
NNE	6	11	10	6	7	7	8	10	9	5	9	8
NE	2	1	3	7	5	5	3	3	5	3	4	5
ENE	1	1	0	1	0	3	2	2	0	3	1	0
E	0	0	0	0	2	1	2	0	1	0	2	1
ESE	2	1	1	2	1	1	1	0	1	2	0	1
SE	3	1	4	3	1	3	3	5	3	6	2	4
SSE	7	10	8	6	9	6	5	4	6	3	9	5
S	4	3	5	4	5	8	10	7	7	5	5	7
SSW	2	3	2	4	3	4	2	6	4	4	1	3
SW	1	1	2	0	1	3	0	1	4	1	3	0
WSW	1	1	0	2	0	1	3	1	0	1	0	1
W	1	1	0	0	0	1	1	2	2	0	0	0
WNW	4	5	6	3	3	1	3	1	2	3	2	2
NW	3	1	2	1	2	3	2	4	3	3	3	3
NNW	4	2	1	3	1	3	4	4	4	5	4	4
CALM	3	5	3	2	7	3	2	2	1	4	5	2

MARCH 1958-1959

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	7	9	8	12	10	9	7	10	10	11	10	10
NNE	7	6	5	7	4	4	6	9	5	10	7	4
NE	2	0	2	2	2	4	3	2	3	2	3	5
ENE	0	3	1	0	0	1	2	0	0	0	2	1
E	2	0	1	1	2	4	2	0	2	0	1	2
ESE	3	3	1	1	1	2	3	4	4	5	4	3
SE	2	4	4	5	2	5	3	3	1	4	3	0
SSE	7	4	10	6	11	7	5	4	7	2	6	9
S	6	7	3	6	6	7	7	7	5	8	5	8
SSW	2	2	1	1	0	1	4	3	4	1	1	0
SW	0	1	3	0	1	2	1	2	2	3	0	0
WSW	1	0	1	3	2	4	3	2	4	1	3	2
W	0	2	2	2	2	0	3	4	2	1	0	1
WNW	6	6	3	4	3	4	0	3	4	3	2	5
NW	6	2	4	3	3	2	4	6	3	7	6	6
NNW	4	4	6	2	7	5	7	3	7	4	4	2
CALM	7	9	7	7	6	1	2	0	1	0	4	4

APRIL 1958-1959

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	6	8	9	10	12	9	6	10	9	10	8	3
NNE	4	6	2	5	3	2	8	5	7	4	2	5
NE	3	1	1	1	2	6	3	6	3	4	4	5
ENE	2	0	2	0	0	5	1	2	4	2	3	3
E	1	3	1	1	1	0	0	2	0	1	1	0
ESE	4	0	0	1	2	0	3	2	1	1	2	1
SE	1	1	4	2	4	4	2	2	1	3	2	2
SSE	6	6	7	3	6	5	7	2	5	4	7	7
S	9	9	10	11	11	10	12	5	10	7	11	12
SSW	3	3	4	2	2	8	5	10	6	7	3	4
SW	2	3	1	2	3	1	2	5	2	4	0	1
WSW	3	2	2	1	0	2	2	2	2	0	1	1
W	1	0	0	0	0	0	0	0	1	1	0	2
WNW	1	5	3	2	3	0	1	0	0	0	2	1
NW	4	2	3	5	2	2	4	5	3	2	1	1
NNW	7	5	7	6	4	4	4	1	3	4	8	8
CALM	3	6	4	8	5	2	0	1	3	6	5	4

MAY 1958-1959

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	5	5	5	3	3	1	4	5	4	3	4	6
NNE	5	2	1	4	6	5	4	3	3	7	3	1
NE	1	3	2	0	2	3	4	3	5	5	5	4
ENE	0	0	0	0	1	1	2	2	3	1	0	0
E	1	2	0	4	2	2	1	2	0	1	1	1
ESE	4	1	3	2	1	3	1	3	3	3	3	3
SE	6	5	5	6	4	5	3	5	6	8	2	3
SSE	10	12	13	11	10	8	9	15	11	12	14	20
S	14	12	12	10	14	13	14	9	12	12	14	8
SSW	5	4	2	3	3	10	9	8	7	4	3	1
SW	0	0	0	1	2	3	3	0	2	1	2	1
WSW	0	0	0	1	0	0	0	1	0	0	0	1
W	0	0	0	1	0	0	0	0	1	0	0	1
WNW	1	0	0	0	1	0	0	0	1	0	0	1
NW	1	1	0	1	2	0	1	1	2	1	3	1
NNW	4	3	2	3	2	4	1	1	1	3	1	2
CALM	5	12	17	12	9	4	6	4	1	1	7	8

Table A1-b. HOURLY FREQUENCY OF WIND DIRECTION, WBAS, TULSA (Anemometer Height = 39 feet)

JUNE 1958-1959

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	1	1	7	1	6	5	4	2	4	3	0	2
NNE	2	3	1	1	4	5	4	6	3	5	3	2
NE	2	1	1	2	0	3	4	3	5	3	2	4
ENE	1	0	0	1	1	0	1	2	2	2	3	1
E	1	0	1	2	1	1	1	1	1	2	2	2
ESE	2	0	3	0	2	5	2	3	3	2	3	3
SE	6	6	5	6	4	0	4	4	8	6	7	5
SSE	17	11	16	12	14	8	7	11	10	17	16	14
S	11	14	10	10	9	15	12	14	15	13	14	15
SSW	2	4	1	2	3	9	11	6	3	3	1	1
SW	0	2	1	2	4	2	2	1	1	0	0	0
WSW	1	1	1	1	1	1	3	2	0	1	0	0
W	0	0	0	0	0	0	1	0	0	0	0	0
WNW	0	1	0	0	0	2	0	0	2	0	0	0
NW	1	0	1	2	2	0	1	3	1	0	1	1
NNW	0	1	3	4	1	1	0	1	0	0	0	0
CALM	13	15	9	14	8	3	3	1	2	3	8	10

JULY 1958-1959

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	4	5	2	4	5	3	5	3	4	5	3	2
NNE	4	2	0	1	5	6	6	6	6	3	4	1
NE	1	0	1	2	2	2	2	5	4	5	4	5
ENE	0	0	0	0	2	1	1	1	2	0	3	3
E	2	2	0	1	0	2	2	2	0	2	2	4
ESE	2	3	2	0	3	0	3	2	1	2	4	5
SE	1	5	6	2	4	5	4	3	0	2	6	6
SSE	16	11	18	14	8	7	7	11	8	14	16	17
S	22	16	11	17	18	11	10	11	13	16	11	10
SSW	1	14	6	3	6	12	13	8	9	5	3	1
SW	1	1	2	2	1	3	3	2	1	2	0	0
WSW	0	1	1	0	0	1	2	3	2	0	0	0
W	0	0	0	0	0	0	0	1	0	0	0	0
WNW	1	1	1	1	1	0	0	0	1	2	0	0
NW	0	0	2	2	1	4	1	0	1	1	0	2
NNW	2	2	3	3	1	2	0	0	0	0	0	1
CALM	5	8	7	10	5	3	3	4	1	3	6	5

AUGUST 1958-1959

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	1	2	3	3	1	3	1	3	4	1	1	2
NNE	3	3	3	2	3	1	3	1	2	6	3	5
NE	1	2	2	3	5	4	4	5	3	5	6	1
ENE	0	1	0	0	0	0	0	0	5	0	1	0
E	1	1	0	2	1	2	1	2	1	0	1	5
ESE	1	3	1	3	1	3	0	2	0	6	3	1
SE	7	8	9	7	5	4	5	9	8	9	11	11
SSE	23	13	15	17	14	12	11	9	12	15	20	20
S	17	15	12	11	13	12	18	10	13	9	9	12
SSW	1	2	2	2	9	14	8	11	6	3	2	1
SW	1	0	0	1	0	1	0	3	1	2	0	0
WSW	0	0	0	0	0	1	1	1	1	0	0	0
W	0	0	0	0	0	0	0	0	1	0	0	0
WNW	0	0	0	1	0	0	2	1	0	1	0	0
NW	1	2	0	0	0	0	0	0	1	1	0	1
NNW	1	3	2	2	2	0	2	2	0	0	0	0
CALM	4	7	13	8	7	5	6	3	4	4	5	3

SEPTEMBER 1958-1959

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	5	4	5	9	6	3	2	4	5	1	5	3
NNE	6	7	5	5	5	8	7	6	5	9	10	6
NE	3	0	0	2	2	2	5	3	3	6	4	5
ENE	0	0	0	1	1	1	0	0	2	1	2	1
E	2	1	0	1	1	0	1	3	2	2	1	3
ESE	1	1	1	0	2	0	1	0	2	2	1	4
SE	7	5	4	6	4	3	3	5	11	7	9	10
SSE	21	20	23	19	14	9	10	10	11	19	17	18
S	8	10	10	5	12	17	16	14	12	7	6	6
SSW	1	2	0	2	1	10	8	9	1	1	1	0
SW	1	0	0	2	0	1	2	2	0	0	0	0
WSW	0	0	0	0	0	1	0	0	0	0	0	0
W	0	0	0	0	0	1	0	0	1	1	0	0
WNW	0	0	0	0	0	0	1	1	0	0	0	0
NW	0	1	0	1	1	0	1	2	1	2	1	2
NNW	0	1	3	0	2	0	0	0	1	0	0	0
CALM	5	8	9	8	9	4	3	1	3	2	3	2

OCTOBER 1958-1959

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	9	9	11	7	7	9	5	8	11	9	9	8
NNE	4	5	3	4	3	3	4	4	3	4	4	2
NE	1	1	0	3	2	2	4	2	0	2	0	0
ENE	1	0	1	1	0	2	1	1	2	2	2	1
E	2	1	2	0	3	1	0	1	0	3	2	2
ESE	0	2	2	3	0	3	1	2	1	2	3	0
SE	8	7	4	7	4	2	2	4	7	13	7	9
SSE	14	9	11	7	12	8	10	11	11	6	14	12
S	4	10	7	10	8	13	16	12	8	8	7	7
SSW	5	2	0	1	3	6	3	5	3	1	2	4
SW	1	1	2	1	2	3	5	2	4	0	1	0
WSW	0	1	1	2	0	0	0	1	0	1	1	0
W	0	1	1	0	0	0	0	0	0	0	1	3
WNW	3	0	1	1	3	0	1	1	0	1	1	2
NW	4	3	4	4	5	2	5	2	4	3	3	4
NNW	2	4	3	4	2	3	4	4	2	1	1	1
CALM	4	6	9	7	8	5	1	2	6	5	4	7

NOVEMBER 1958-1959

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	7	9	9	9	7	7	6	3	4	3	3	6
NNE	2	1	3	0	3	4	5	5	5	3	5	4
NE	2	1	0	0	0	0	1	1	3	2	1	1
ENE	0	0	1	1	0	0	0	1	0	2	2	0
E	0	0	0	0	1	1	1	1	0	0	0	1
ESE	0	0	0	0	0	0	0	0	0	0	0	0
SE	3	5	5	4	3	0	0	1	2	7	4	4
SSE	13	10	11	13	14	15	6	7	8	9	12	8
S	8	10	9	13	11	11	13	12	9	10	11	12
SSW	5	4	4	0	1	3	8	8	7	5	6	3
SW	1	2	0	0	0	4	8	7	5	3	3	4
WSW	2	3	2	1	2	0	0	2	3	1	0	1
W	2	1	1	2	1	1	0	2	1	2	0	1
WNW	2	0	2	2	0	1	4	2	2	4	5	1
NW	3	3	5	6	6	4	2	3	5	3	1	2
NNW	0	2	2	3	2	3	4	4	4	3	1	2
CALM	10	9	6	6	9	6	2	1	2	3	6	9

Table A2-a. HOURLY FREQUENCY OF WIND DIRECTION, TMT, TULSA (Anemometer Height = 215 feet)

DECEMBER 1957-1958

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	4	1	1	0	2	2	3	2	1	1	3	4
NNE	1	0	1	1	1	2	0	1	0	0	0	0
NE	0	0	0	0	0	0	1	0	0	0	0	0
ENE	0	1	0	0	0	0	0	0	0	0	0	0
E	0	0	0	1	0	0	0	2	1	1	0	0
ESE	0	1	0	0	1	1	2	1	0	1	0	0
SE	0	0	1	1	2	1	1	1	2	2	1	0
SSE	2	2	4	2	1	1	0	0	2	4	5	3
S	6	6	5	5	7	5	6	7	7	3	3	6
SSW	3	8	6	6	4	6	7	7	4	7	8	6
SW	5	2	3	3	2	1	0	1	2	1	3	2
WSW	1	1	1	2	1	2	2	1	3	2	0	3
W	1	0	1	1	3	2	3	4	3	4	4	1
WNW	5	2	2	2	1	2	1	1	0	0	1	2
NW	2	4	4	4	3	2	2	2	3	2	2	2
NNW	1	3	2	3	3	2	2	1	2	3	1	2
CALM	0	0	0	0	0	1	1	0	1	0	0	0
MISSING	0	0	0	0	0	1	0	0	0	0	0	0

JANUARY 1958

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	2	4	4	2	4	6	4	4	4	3	3	2
NNE	2	1	2	2	1	1	1	2	4	2	1	2
NE	1	0	1	1	0	0	0	0	0	2	2	0
ENE	1	1	0	0	1	0	0	0	1	1	0	3
E	1	2	0	0	0	0	0	1	0	0	2	0
ESE	0	1	1	1	0	1	1	0	1	1	2	0
SE	3	1	1	3	2	2	2	3	2	6	6	4
SSE	6	5	5	3	6	3	3	3	5	3	1	4
S	0	2	2	3	3	4	2	4	4	2	2	1
SSW	3	2	2	1	0	0	6	4	2	3	3	4
SW	2	2	2	2	3	1	2	0	2	0	1	2
WSW	0	0	3	1	2	2	1	1	0	0	0	0
W	1	1	0	0	0	2	1	2	1	1	3	2
WNW	1	0	1	3	1	1	1	2	2	3	2	0
NW	5	6	5	4	5	3	2	2	2	1	0	3
NNW	3	3	2	4	1	4	5	3	1	3	3	4
CALM	0	0	0	1	2	0	0	0	0	0	0	0
MISSING	0	0	0	0	0	1	0	0	0	0	0	0

FEBRUARY 1958

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	4	3	4	2	2	3	4	7	5	5	6	5
NNE	7	7	6	4	2	4	4	3	3	4	2	3
NE	1	1	1	2	4	3	1	0	2	1	4	3
ENE	0	0	1	1	1	0	2	1	1	1	1	0
E	1	0	1	1	0	0	0	0	0	0	0	1
ESE	0	0	0	2	1	1	0	1	0	0	0	0
SE	0	1	0	0	0	0	0	0	0	2	1	0
SSE	2	1	0	1	1	2	4	3	4	3	2	2
S	1	2	2	2	2	2	1	2	1	0	1	2
SSW	1	0	1	2	2	2	2	1	1	1	2	2
SW	1	2	1	0	1	2	1	2	2	2	1	0
WSW	0	1	0	1	1	0	0	0	0	0	0	0
W	0	2	1	0	0	1	1	1	1	1	0	1
WNW	2	0	4	2	2		1	1	0	1	2	1
NW	2	2	1	1	0	0	1	1	2	1	1	1
NNW	1	1	0	2	2	1	1	0	1	1	0	2
CALM	0	0	0	0	0	0	0	0	0	0	0	0
MISSING	5	5	5	5	5	5	5	5	5	5	5	5

MARCH 1958-1959

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	10	12	12	11	11	10	13	13	8	10	12	9
NNE	8	3	5	5	5	4	3	1	6	8	8	7
NE	1	5	4	4	3	2	0	3	2	1	2	4
ENE	1	1	1	0	1	1	2	0	2	2	1	2
E	3	1	1	2	2	1	1	3	2	0	1	1
ESE	3	1	2	1	2	5	2	3	2	5	6	3
SE	2	4	4	7	2	3	6	2	4	2	1	2
SSE	3	5	5	3	5	0	1	2	2	3	1	6
S	10	8	6	8	11	12	10	9	8	7	9	7
SSW	0	1	2	2	1	3	4	2	2	1	1	0
SW	2	2	1	1	1	1	0	1	1	2	1	0
WSW	0	0	2	1	1	3	3	3	1	2	2	2
W	2	1	1	1	2	2	2	5	6	1	0	1
WNW	4	3	1	2	0	1	2	4	3	5	2	2
NW	3	1	4	4	3	1	3	2	3	5	5	7
NNW	5	8	5	3	4	6	3	3	4	3	5	4
CALM	0	0	0	0	1	0	0	0	0	0	0	0
MISSING	5	6	6	7	7	7	7	6	6	5	5	5

APRIL 1958-1959

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	6	6	8	11	6	10	7	11	7	9	5	6
NNE	5	5	5	5	8	3	4	6	10	8	7	7
NE	4	5	3	1	1	4	2	1	2	3	6	2
ENE	1	2	1	1	1	2	1	2	4	2	0	2
E	2	2	1	2	2	2	3	2	0	1	0	1
ESE	3	1	0	2	0	3	1	2	1	2	2	2
SE	1	1	5	2	2	2	3	1	2	2	0	1
SSE	4	3	1	2	6	2	4	4	6	5	9	6
S	11	11	10	11	10	12	13	11	11	5	11	12
SSW	4	6	9	6	8	9	7	8	4	11	5	4
SW	2	0	2	2	1	1	2	3	3	2	0	2
WSW	4	2	1	1	1	1	1	1	0	0	0	0
W	1	1	1	1	0	0	2	0	2	2	1	4
WNW	3	1	1	2	2	2	2	1	1	2	4	2
NW	5	8	3	5	3	1	2	3	3	3	4	5
NNW	4	6	9	6	9	6	6	4	4	3	6	4
CALM	0	0	0	0	0	0	0	0	0	0	0	0
MISSING	0	0	0	0	0	0	0	0	0	0	0	0

MAY 1958-1959

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	6	3	6	4	6	4	3	2	3	3	4	5
NNE	3	7	3	3	4	3	7	4	4	4	5	3
NE	0	1	2	2	1	2	2	4	1	5	5	4
ENE	2	0	0	0	0	1	0	1	3	1	1	0
E	1	2	1	0	3	3	0	1	2	1	1	2
ESE	5	2	1	1	1	2	2	2	1	3	1	2
SE	4	1	5	6	2	1	2	2	6	3	7	6
SSE	11	7	9	7	10	6	8	9	6	7	10	12
S	13	18	15	13	11	14	15	13	15	17	12	10
SSW	2	7	6	6	7	9	9	8	2	3	3	2
SW	1	1	2	2	1	2	0	0	4	0	1	1
WSW	0	0	1	2	1	2	1	1	1	0	0	0
W	0	0	0	1	2	0	0	1	0	0	0	1
WNW	0	1	0	1	1	0	0	1	1	1	0	1
NW	2	0	0	1	0	2	2	0	1	2	1	3
NNW	2	1	0	2	1	1	2	3	1	2	0	0
CALM	0	0	0	0	0	0	0	0	0	0	0	0
MISSING	10	11	11	11	11	10	9	10	11	10	11	10

Table A2-b. HOURLY FREQUENCY OF WIND DIRECTION, TMT, TULSA (Anemometer Height = 215 feet)

JUNE 1958-1959

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	1	2	5	5	7	5	5	6	3	2	3	0
NNE	4	2	3	1	2	3	3	3	4	5	4	6
NE	2	2	1	1	0	1	3	0	2	3	2	1
ENE	0	2	1	0	0	0	3	3	2	2	3	3
E	4	2	0	1	3	2	0	2	2	0	0	3
ESE	4	1	3	4	3	2	1	3	3	5	2	3
SE	5	5	6	3	2	1	4	3	3	2	6	5
SSE	11	7	6	9	3	4	3	5	5	11	14	14
S	15	21	13	12	13	13	14	13	15	15	14	12
SSW	2	3	8	4	7	9	5	6	4	2	1	1
SW	0	1	1	2	2	1	2	1	0	1	0	1
WSW	0	0	1	0	0	0	2	0	1	0	0	0
W	0	0	0	1	0	2	2	2	0	2	0	0
WNW	0	0	1	1	0	0	0	0	1	0	0	0
NW	0	1	0	0	2	2	0	1	2	0	0	0
NNW	1	0	0	3	2	3	2	1	1	0	1	0
CALM	0	0	0	0	0	0	0	0	0	0	0	0
MISSING	11	11	11	13	14	12	11	11	12	10	10	11

JULY 1958

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	0	1	1	1	2	1	1	2	1	0	1	0
NNE	2	1	1	2	2	2	2	2	4	2	0	2
NE	1	0	0	0	2	2	0	0	1	1	3	3
ENE	1	1	0	0	1	0	0	0	0	1	0	0
E	1	0	2	1	0	0	1	0	0	0	0	0
ESE	1	0	1	1	1	1	1	0	2	2	1	4
SE	0	1	1	1	0	1	1	0	0	0	1	1
SSE	5	5	1	1	1	0	0	1	3	0	7	6
S	8	7	10	9	10	7	8	7	5	11	7	8
SSW	2	4	2	3	2	6	5	6	7	3	0	0
SW	0	0	1	0	0	2	2	0	1	1	0	0
WSW	0	0	0	1	0	0	0	1	1	1	0	0
W	0	0	0	0	0	0	1	0	0	0	0	0
WNW	0	0	0	0	0	0	0	0	0	0	0	0
NW	0	0	0	1	0	0	0	0	0	0	1	0
NNW	0	1	1	1	0	1	1	1	0	1	0	0
CALM	0	0	0	0	0	0	0	0	0	0	0	0
MISSING	10	10	10	9	10	8	8	10	8	10	10	10

AUGUST 1958-1959

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	2	1	3	4	2	1	1	0	1	2	1	2
NNE	3	5	4	5	3	3	3	3	3	7	4	3
NE	1	2	4	2	5	5	3	6	5	4	5	2
ENE	2	0	0	1	2	1	2	1	1	0	4	4
E	1	3	2	1	2	0	3	0	3	2	0	4
ESE	2	2	1	3	2	1	0	2	1	2	2	0
SE	2	0	2	1	1	2	2	2	5	5	9	4
SSE	13	9	5	3	5	3	2	5	2	5	7	11
S	22	17	17	19	11	14	12	13	8	16	19	18
SSW	5	11	11	11	10	12	16	15	19	11	5	5
SW	5	4	5	5	11	9	8	4	3	1	0	5
WSW	0	0	1	2	1	3	5	4	2	1	1	0
W	0	1	1	0	0	0	2	3	1	2	0	0
WNW	0	0	0	0	0	0	0	1	2	0	0	0
NW	0	2	0	0	1	1	1	0	0	0	0	0
NNW	0	0	1	0	0	0	1	1	1	0	1	0
CALM	0	0	0	0	0	0	0	0	0	0	0	0
MISSING	4	5	5	5	6	7	1	2	5	4	4	4

SEPTEMBER 1958-1959

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	7	4	4	4	4	4	3	3	2	2	4	4
NNE	0	1	1	5	2	3	2	2	3	5	6	2
NE	3	2	2	5	5	1	5	2	4	3	0	3
ENE	2	1	2	0	1	4	0	3	4	4	6	4
E	2	3	4	1	2	0	1	3	0	2	0	4
ESE	1	1	1	1	1	1	0	0	1	1	1	2
SE	5	2	2	3	3	2	3	1	4	5	4	3
SSE	5	7	8	9	8	4	3	7	3	7	16	11
S	16	19	16	13	11	16	8	11	14	14	7	14
SSW	8	10	8	8	10	10	15	15	11	7	4	3
SW	2	0	1	1	3	4	9	3	1	0	1	1
WSW	0	1	1	1	1	0	2	0	2	0	0	0
W	0	1	0	0	0	1	0	0	0	1	1	0
WNW	0	0	1	0	0	1	0	0	1	0	0	0
NW	0	0	0	0	1	0	0	2	1	0	0	0
NNW	0	0	1	1	0	0	1	0	1	0	1	0
CALM	0	0	0	0	0	0	0	0	0	0	0	0
MISSING	9	8	8	8	8	9	8	8	8	9	9	9

OCTOBER 1958-1959

Direction	Hour											
	0	2	4	6	8	10	12	14	16	18	20	22
N	1	0	4	4	4	2	3	2	1	2	3	2
NNE	3	5	3	2	2	4	1	1	2	3	3	3
NE	2	2	2	4	2	2	3	3	2	0	1	1
ENE	1	2	2	0	1	1	2	2	2	2	3	1
E	0	0	0	0	1	1	0	0	0	2	1	1
ESE	2	1	0	2	2	0	0	0	2	2	1	4
SE	4	2	3	1	2	1	0	1	3	2	2	2
SSE	3	4	3	4	3	5	2	3	3	6	4	4
S	6	7	9	9	11	9	12	8	7	8	10	8
SSW	6	6	5	4	4	7	7	7	8	6	6	2
SW	2	2	2	2	2	3	4	4	2	1	0	3
WSW	1	0	0	1	1	1	1	4	1	1	0	0
W	1	1	0	0	0	2	1	0	0	0	0	2
WNW	0	1	0	0	0	1	0	0	0	0	0	0
NW	3	0	0	2	1	1	1	1	0	0	1	2
NNW	1	3	3	2	2	0	2	4	5	3	1	1
CALM	0	0	0	0	0	0	0	0	0	0	0	0
MISSING	26	26	26	25	24	22	23	22	24	24	26	26

Table A3. DEPARTURES FROM NORMAL, WBAS, TULSA

MONTH	TEMPERATURE DEPARTURE (°F)	PRECIPITATION DEPARTURE (Inches)	ABNORMALITY (Wind, Weather, Precipitation, etc.)
Dec. 1957	+5.2	-0.25	
Jan. 1958	+1.2	-0.20	
Feb. 1958	-6.9	-0.71	Cloudy; record low pressure.
March 1958	-7.6	+3.53	Cloudy; excessive precipitation and snow.
April 1958	-1.7	+0.14	
May 1958	+2.8	-1.08	
June 1958	+1.2	-2.07	Record low temperature for 4 days.
July 1958	-0.6	+0.64	
Aug. 1958	-1.2	+0.35	
Sept. 1958	+0.8	-0.64	
Oct. 1958	-1.1	-2.88	Very little precipitation.
Nov. 1958	+3.9	-1.01	
Dec. 1958	-3.5	-0.87	Extended period (11 days) of cold temperatures; excessive snow.
Jan. 1959	-3.9	-1.21	Excessive snow.
Feb. 1959	-0.6	+0.12	Excessive snow.
March 1959	+1.6	+0.41	
April 1959	+0.3	-2.79	Very little precipitation.
May 1959	+3.3	+1.89	
June 1959	-0.4	-1.85	
July 1959	-3.8	+7.16	Excessive precipitation.
Aug. 1959	-0.2	-1.10	Very little precipitation; very high humidities.
Sept. 1959	+0.2	+3.17	Excessive precipitation late in month.
Oct. 1959	-3.7	+5.99	Excessive precipitation early in month.
Nov. 1959	-5.1	-0.92	

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